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Report FE 218-7

AIR HEATER EXPERIMENT

The Marquardt

Facilities Engineering Division
Van Nuys, California

December 30, 1960

The facility criteria experiment reported herein resulted from a project sponsored by the Air Research and Development Command under Contract AF 33(616)-6214

Report FE 218-7

AIR HEATER EXPERIMENT

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ABSTRACT

The test program described in this report was designed to determine the feasibility of using a vitiated air heater for the PLUTO facility from the standpoint of burner stability and combustion efficiency over a wide range of operating conditions. The heater was evaluated at design pressures and temperatures consistent with the proposed testing envelope using liquid propane fuel. Combustion pressures were varied from 42 to 491 psia and air weight flows from 15 to 216 pounds per second. Stable combustion was found to exist under all operating conditions. Flow mixing devices were evaluated. Performance of 80-octane fuel was investigated. A combustion chamber flow recirculator and three fuel injection configurations were evaluated. Temperature profiles across the outlet proved relatively flat. The feasibility of using this burner for PLUTO facility air heating was established.

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1.0 SUMMARY AND CONCLUSIONS

The vitiated air heater is suitable for use as the air heater in the PLUTO facility. Examination of the burner interior after the test program showed that there were no carbon deposits left in the burner or on the exit orifice after some 2000 gallons of propane fuel had been consumed. Temperature control was precise and response extremely rapid. At no time did the burner tend to become unstable, even during rapid fuel and airflow transients while coming up to test points. Gas analysis indicated no CO was present in the exhaust gas stream with either 80-octane or propane as the fuel (Figure 1). Temperature profiles were generally flat across the burner discharge with the final configuration, (Figure 2). Both hydrogen ignitors and spark plugs were successful in igniting the burner. The use of one turbulator in the upstream position proved the most effective. A combustion chamber flow recirculator proved ineffective.

Combustion efficiencies ranged from 82% to 98%. showing a maximum at values of $\frac{V^*}{DP} \approx 4\text{-}5$ (See Figure 1).

Although the bulk of the documentation points have lower-than-optimum values of $\frac{V}{DP}$, optimum sizing of the full scale PLUTO vitiated air heater will be made. The inherent stability of this heater, together with its transient capabilities, provide a flexible, efficient, and most economical solution to the air heating problem. Therefore, the stored energy type heater currently specified for transient heating in the preliminary design criteria will be eliminated to provide substantial savings in facility cost.

*Modified Dezubay number (See Paragraph 5.1)

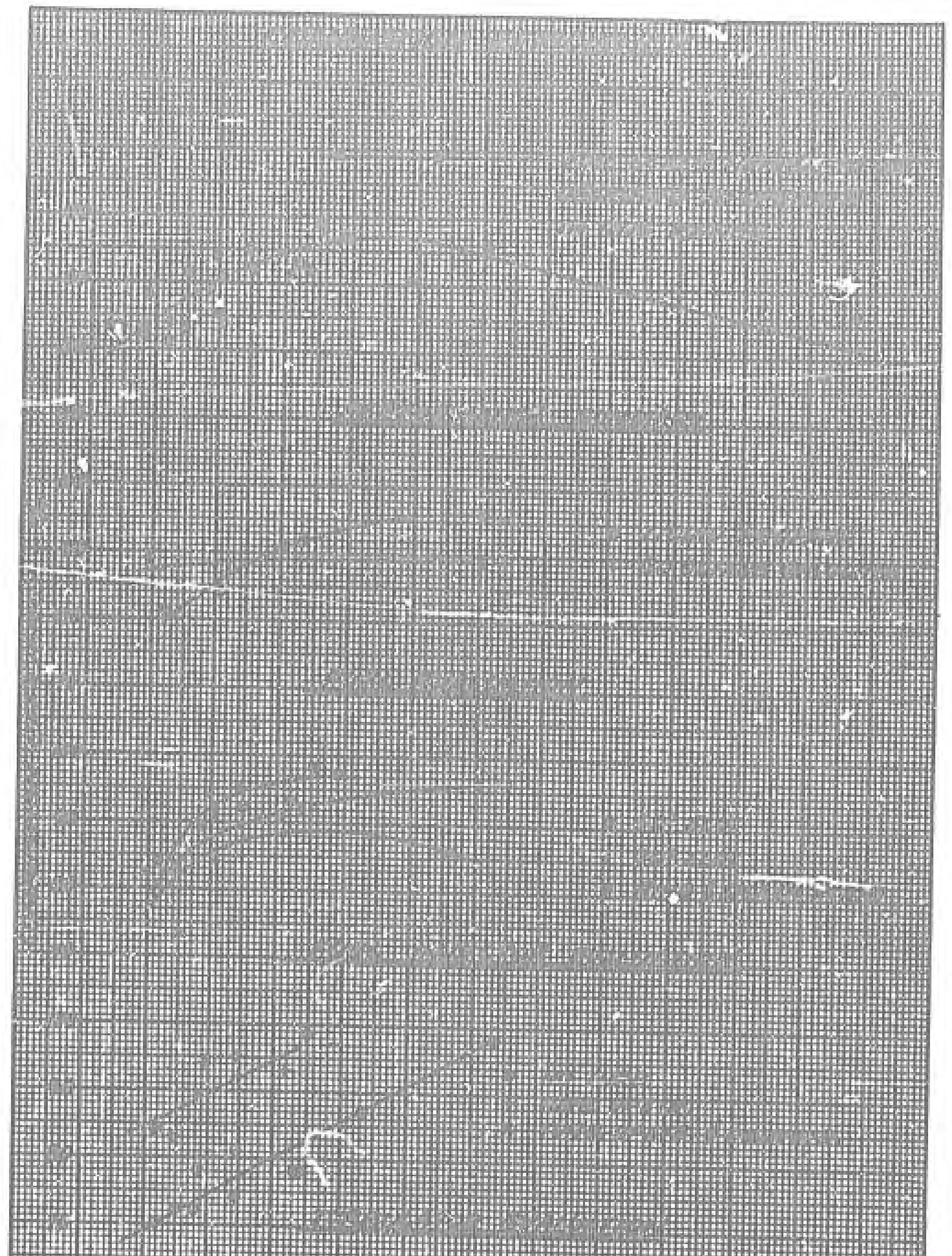

FIGURE 1

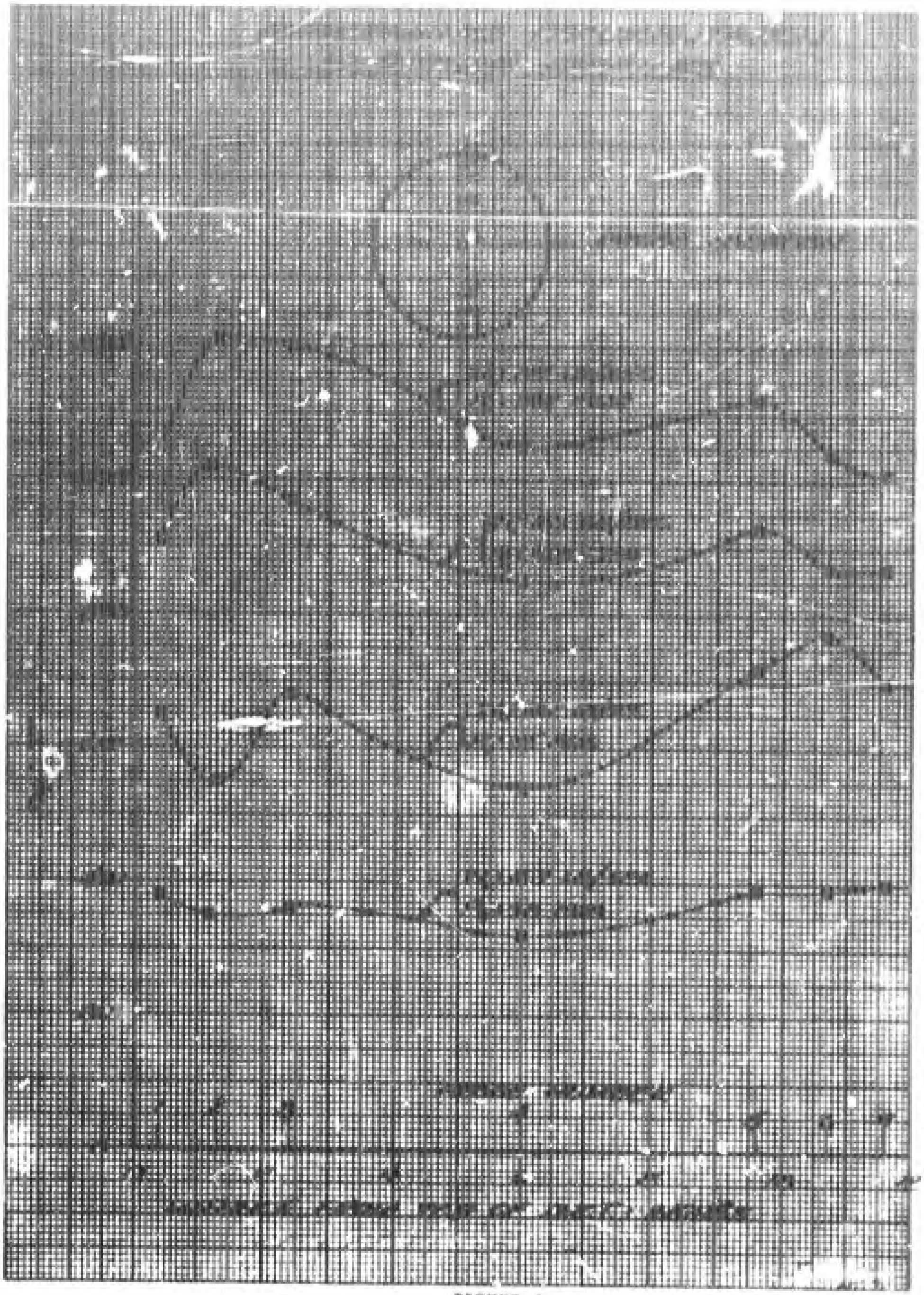

FIGURE [illegible]

2.0 INTRODUCTION

2.1 Prior to the 1960 effort, the PLUTO flight engine test facility preliminary design specified a vitiated air heater to provide the required very high mass flows (2100 pps at 1100°F and 610 psig). The vitiated air heating approach was selected because of the large cost savings over stored energy or indirect-type heaters. In order to assure the feasibility of such a large vitiated air heater, an experimental test program was authorized during 1960 using a scale model based upon the Marquardt Sudden Expansion (SUE) burner.

2.2 The objectives of this test program were

a) Design, fabricate and test a high-pressure direct-burning type heater that will serve as a scale model for construction of the full scale PLUTO facility air heater.

b) Determine the most suitable burner configuration (fuel injectors, flow mixer location, etc.) to obtain the highest efficiency, good outlet temperature profiles, and no objectionable exhaust products.

c) Evaluate this most suitable configuration over the whole range of the required facility performance envelope, including both steady-state and transient conditions.

d) Determine the above using propane and one alternate hydrocarbon fuel.

3.0 PROCEDURE

3.1 The test program was divided into two phases:

a) Determination of a suitable burner configuration. Items considered in this phase were fuel injector design and turbulator (flow mixing device) location.

b) Evaluation of the most suitable configuration over the whole range of required performance. During this phase, gas samples were taken from the burner discharge gases and analyzed to determine the percentages of CO_2, CO, N_2, O_2, and raw fuel present in the gases.

3.2 A total of 37 runs were made. Of this total the first 22 runs constituted the phase a) portion of the program. Five of the remaining 15 runs were used to evaluate the performance of the configuration. The remaining 10 runs were used to recheck data obtained during the phase a) part of the program and to evaluate a spark plug as an ignition source.

3.3 The tests were divided into five groups:

a) recirculator evaluation,

b) turbulator evaluation,

c) fuel injector evaluation,

d) final model configuration performance documentation, and

e) 80-octane gasoline evaluation.

In each group, the heater was operated at a number of flows, pressures, and temperatures which simulated a portion of the required operating envelope. The actual values of flow, temperature and pressure used on each test are shown in TABLE I. In the performance documentation, the test points cover the entire required operating envelope except the

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TABLE I

TEST POINT SUMMARY

Group No.	Configuration: Exit Orifice 7.50	7.12	6.50	4.50	3.78	Turbulator: upstream	downstream	none	Inlet Reducer: in	out	Fuel Injector: 60° slot	90° slot	ring and sp. plate	Fuel: liq propane	80-octane	P_{T4}** Psia	W_a lb/sec	T_{T4}** °F Avg.
*I		X						X		X	X			X		334	123	890
II		X						X		X	X			X		329	185	601
		X						X		X	X			X		264	153	608
		X						X		X	X			X		220	123	598
		X						X		X	X			X		161	95	586
		X						X		X	X			X		119	72	611
TURBULATOR EVALUATION	X							X		X	X			X		338	203	939
	X							X		X	X			X		266	150	926
	X							X		X	X			X		191	119	825
	X							X		X	X			X		156	96	938
	X							X		X	X			X		110	72	952
	X					X				X	X			X		339	210	953
	X					X				X	X			X		259	157	895
	X					X				X	X			X		204	128	884
	X					X				X	X			X		164	102	874
		X				X				X	X			X		334	190	602
		X				X				X	X			X		270	155	604
		X				X				X	X			X		214	130	586
		X				X				X	X			X		164	101	615
		X				X				X	X			X		114	74	598
		X				X	X			X	X			X		324	195	613
		X				X	X			X	X			X		114	83	[illegible]

TABLE I - continued

TEST POINT SUMMARY

Group No.	Configuration: Exit Orifice 7.50	7.12	6.50	4.50	3.78	Turbulator: upstream	downstream	none	Inlet Reducer*: in	out	Fuel Injector: 60° slot	90° slot	ring and sp. plate	Fuel: liq propane	80-octane	P_{T4}** Psia	W_a lb/sec	T_{T4}** °F Avg.
III FUEL INJECTOR EVALUATION		X				X				X		X		X		324	187	587
		X				X				X		X		X		206	121	611
		X				X				X		X		X		122	73	617
	X					X				X		X		X		332	177	1007
	X					X				X		X		X		208	127	872
	X					X				X		X		X		109	75	995
				X		X				X			X	X		359	61	1125
				X		X				X			X	X		166	25	1107
				X		X				X			X	X		103	15	1124
	X					X				X			X	X		324	216	611
	X					X				X			X	X		117	68	808
IV PERFORMANCE EVALUATION	X					X				X		X		X		348	177	1097
	X					X				X		X		X		116	82	585
			X			X				X		X		X		28	15.7	370
			X			X				X		X		X		35	14.2	693
			X			X				X		X		X		491	179	1152
			X			X				X		X		X		459	188	717
				X		X				X		X		X		362	60.5	1070
				X		X				X		X		X		170	25.7	1092
				X		X				X		X		X		100	19.6	1030
					X	X				X		X		X		450	50.5	1106
V FUEL EVAL.	X					X				X		X			X	338	213	594
	X					X				X		X			X	114	61	955
				X		X				X		X			X	363	58	1176
				X		X				X		X			X	169	30	1108

* Use of recirculator discontinued after first run due to failure of cooling.
** Measured 8 diameters downstream of step.

3.0 PROCEDURE - continued

3.3 continued

maximum pressure point, 545 psia. This point was not attainable within the air system limits of MJL-VN. By the time the heater had been ignited and air flow brought up to the maximum, the air storage pressure had dropped below that required to obtain the high pressure points. Maximum combustion chamber pressure obtained was 491 psia.

3.4 Two fuels were used in the test program, liquid propane and 80-octane gasoline. All configuration evaluation tests and the final configuration performance documentation were run using liquid propane. The 80-octane gasoline was used on four runs to provide data for comparison of heater performance on each fuel.

3.5 All tests were run using ambient temperature inlet air from the 600 psi air storage system. Air flow was controlled by positioning a 10-inch rotovalve in the air supply line to give the desired pressure at the heater exit. Different pressure vs. flow characteristics were obtained by using different size exhaust orifices with the heater.

3.6 The desired heater exit gas temperature was obtained by regulating the fuel flow into the burner with a manually controlled, pneumatically-operated Annin valve.

3.7 The recirculator evaluation tests were terminated after two runs due to recirculator overheating. Data was obtained from only one run.

4.0 APPARATUS

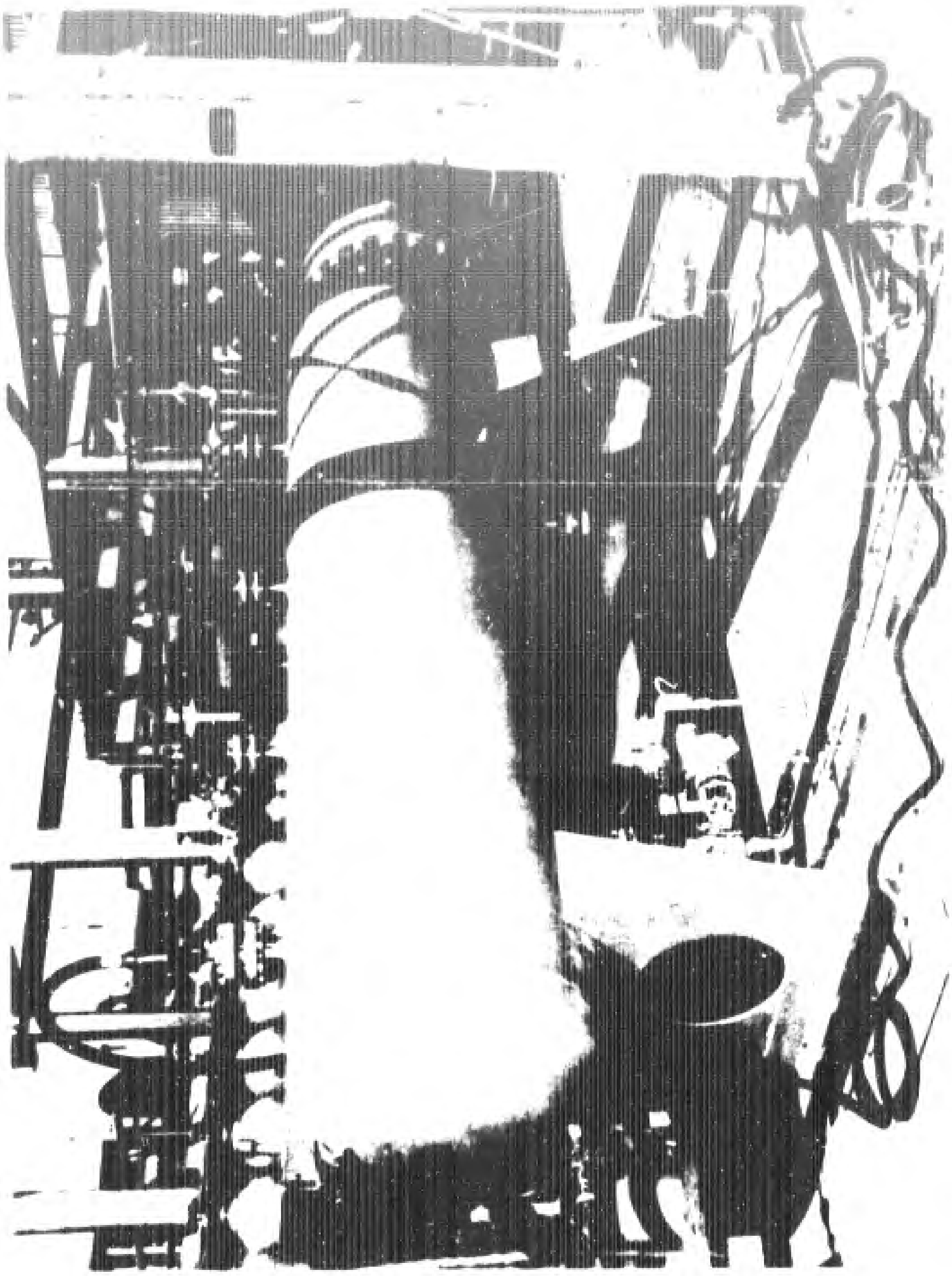
4.1 MJL-VN Facilities

The test were conducted in Cell 7 at MJL-VN. This cell is designed for aerodynamic and combustion testing. The air supply system was modified to provide a connection directly to the 600 psi tanks so that air weight flows up to 250 lbs/sec at 600 psi are available for blowdown testing. This is shown on Drawing 702951.

An independent fuel system was provided consisting of a 300 gallon run tank, fuel metering apparatus, and fuel flow control valve. This is shown on Drawing 702954. A fuel tank pressurizing system allows the tank to be pressurized with nitrogen up to 1000 psi. The fuel system will handle liquid propane and all common hydrocarbon fuels. The fuel system is shown in Figures 3 and 4. A hydrogen-air ignition system was initially provided for combustion tests (Figure 5). Later an aircraft-type spark plug was installed in each of three positions located axially along the length of the combustion chamber just downstream of the step. In each case the plug was installed with the electrode, flush with the inner wall.

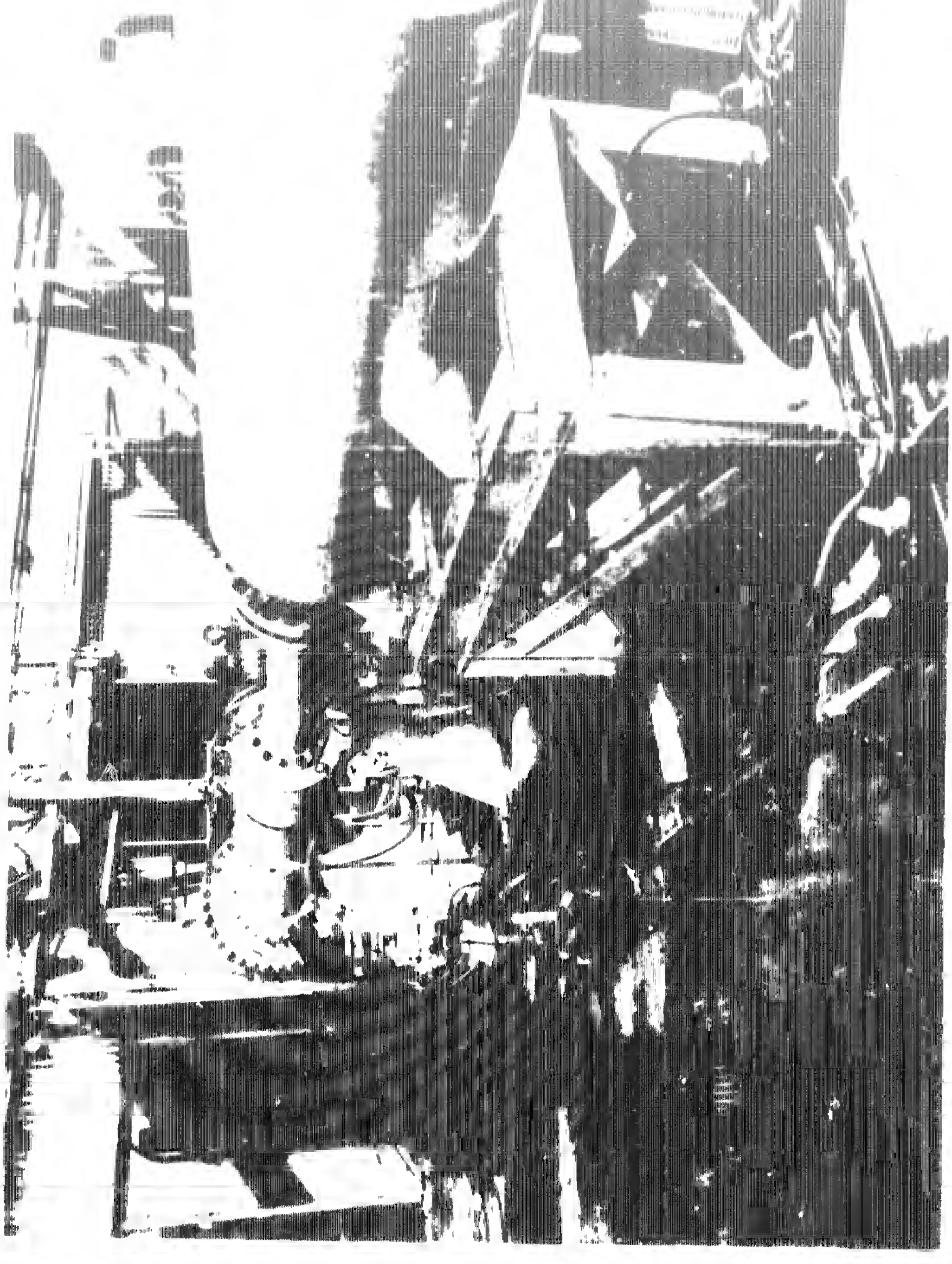
A control shed contains the fuel system and ignition system controls and the test item instrumentation. Air flow is controlled from the Cell 2 control room. Telephone communications is provided between the Cell 2 and Cell 7 control shed. The control shed is shown in Figure 6.

For this test, the cell was operated on an ambient inlet temperature blowdown basis with the burner exhaust open to atmosphere through the facility exhaust ducting. Air was used from the 600 psi storage system to provide the pressures and flows required.



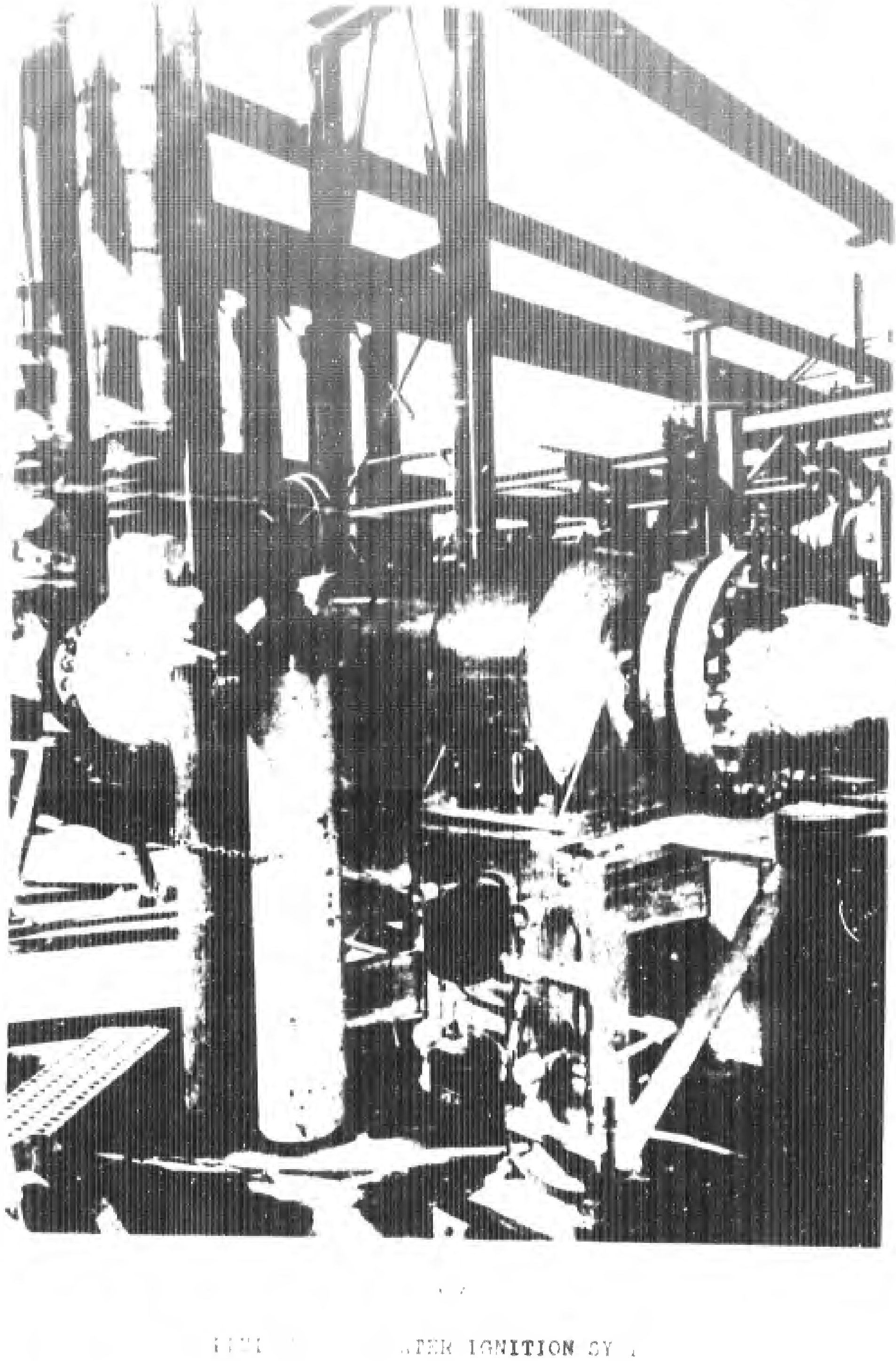
FUEL TANK

Figure 3



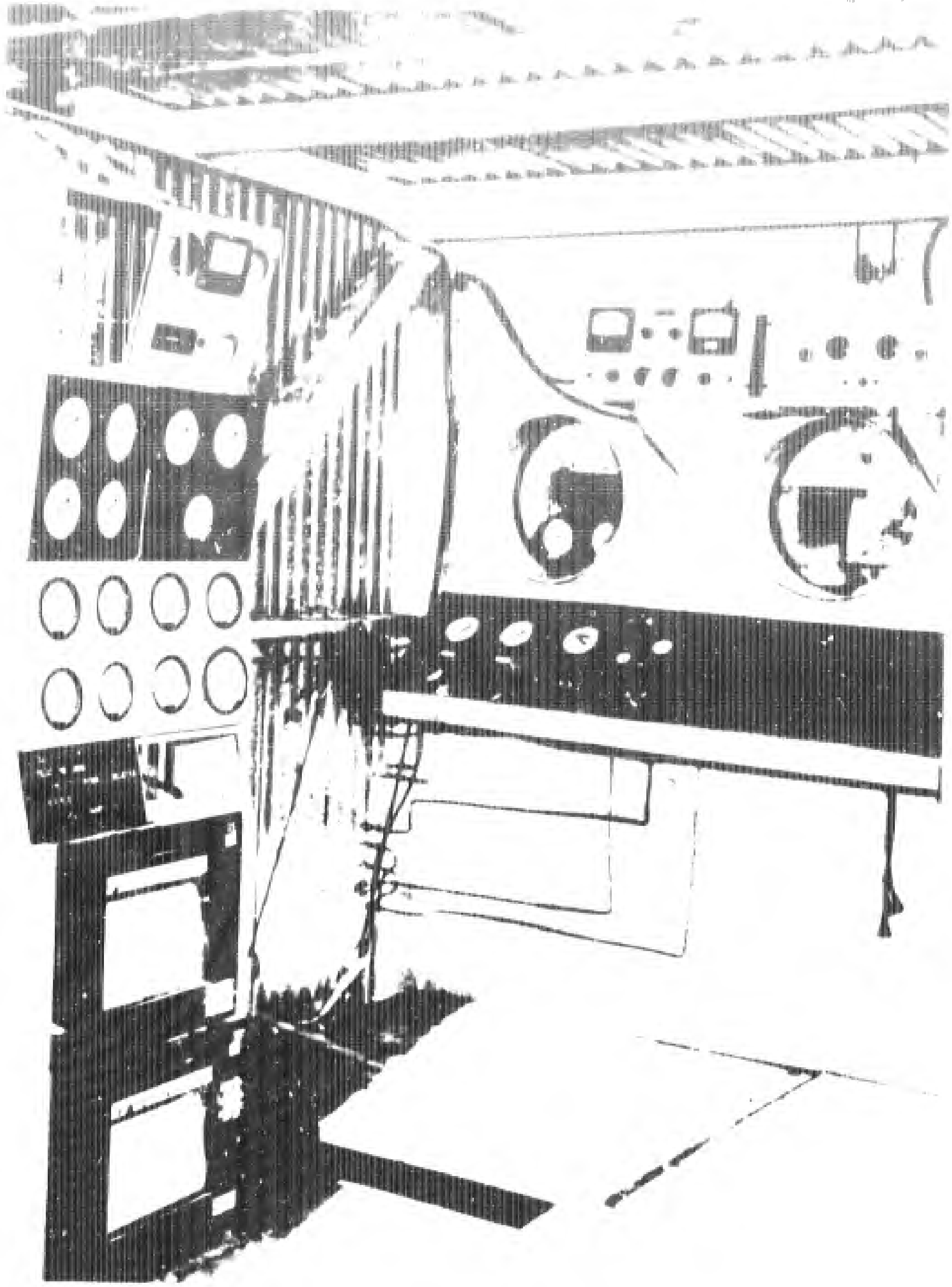
PLUTO MODEL HEATER AND FUEL CONTROL PLUMBING

Figure 4



[illegible] ATER IGNITION SY [illegible]

Figure 5



CONTROL SHED

Figure 6

4.0 APPARATUS - continued

4.2 SUE Burner

The SUE burner used in the test consisted of an 8 inch diameter inlet section, a 12 inch diameter combustion chamber, and an 8 inch diameter exhaust pipe. Photographs of the burner are shown in Figures 7, 8, 9, 1 and a section is shown in Figure 11. The burner was made up of five spool sections. The upstream section consisted of a straight 8 inch diameter pipe with provisions for measuring inlet air total temperature and pressure. This section was not water cooled. The second section (which is the combustion chamber) consisted of an 8 inch diameter inlet, expansion plate, a short 12 inch diameter section, fuel injectors, and ignitors. The third section consisted of a plain 12 inch pipe spool. The fourth section consisted of a 12 inch pipe spool reduced to 8 inch diameter at the downstream end. This section contained temperature and pressure rakes. The fifth section was plain 8 inch pipe. Sections 2, 3, and 4 were water cooled.

Three types of fuel injectors were tested; a 90° slot type, a 60° slot type, and a ring-splash plate type. The nozzles were inserted through Swagelok* fittings in the expansion plate. Photos of the fuel nozzles are shown in Figures 12, 13, 14, and 15.

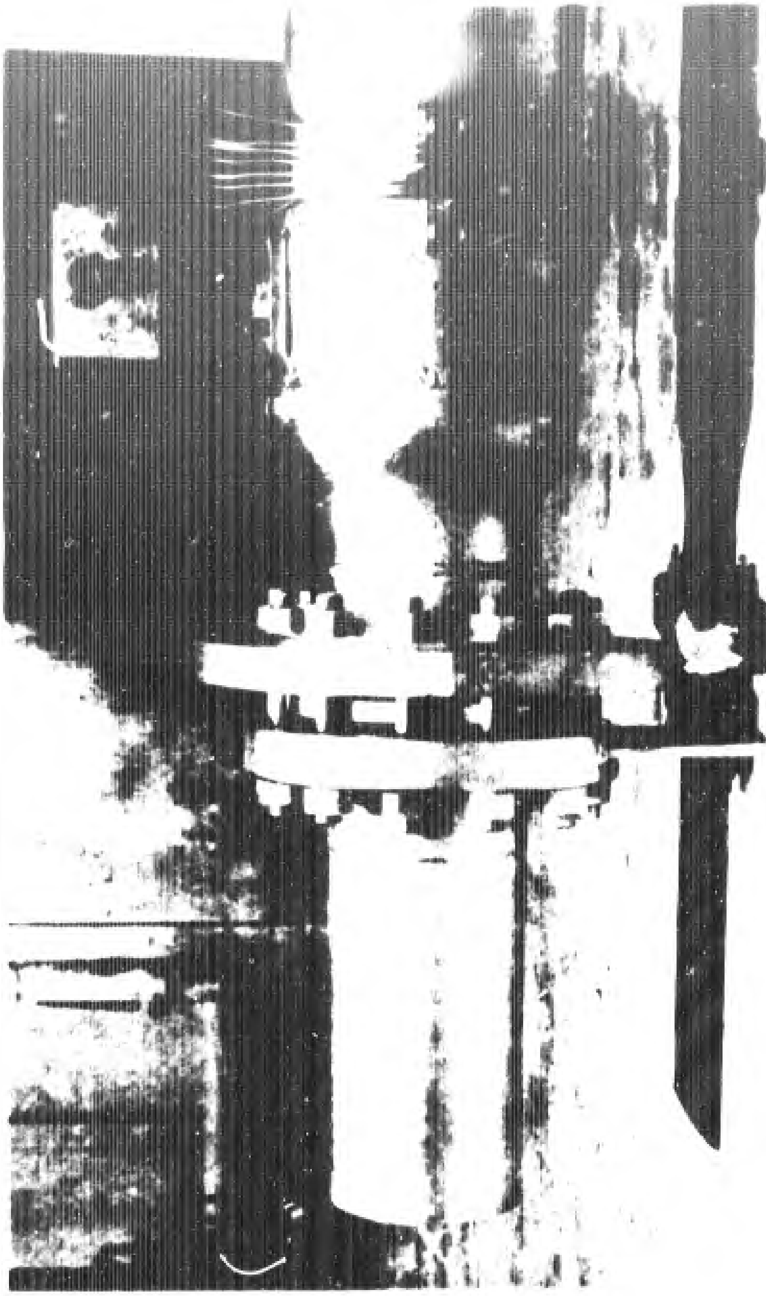
Flow mixing devices (turbulators) were tested in two locations, downstream of the second section, and downstream of the third sections. The turbulators were water cooled orifice plates with 8 inch diameter openings. They were installed between the spool section flange faces. The turbulator is shown in Figure 16. (The carbon deposit resulted from 80-octane testing.)

A flow recirculator was also evaluated. It consisted of a water cooled cylinder inserted into the combustion chamber in the second spool section. The recirculator is shown in Figure 17.

*Swagelok is a registered trademark of the Crawford Fitting Co., Cleveland, Ohio.

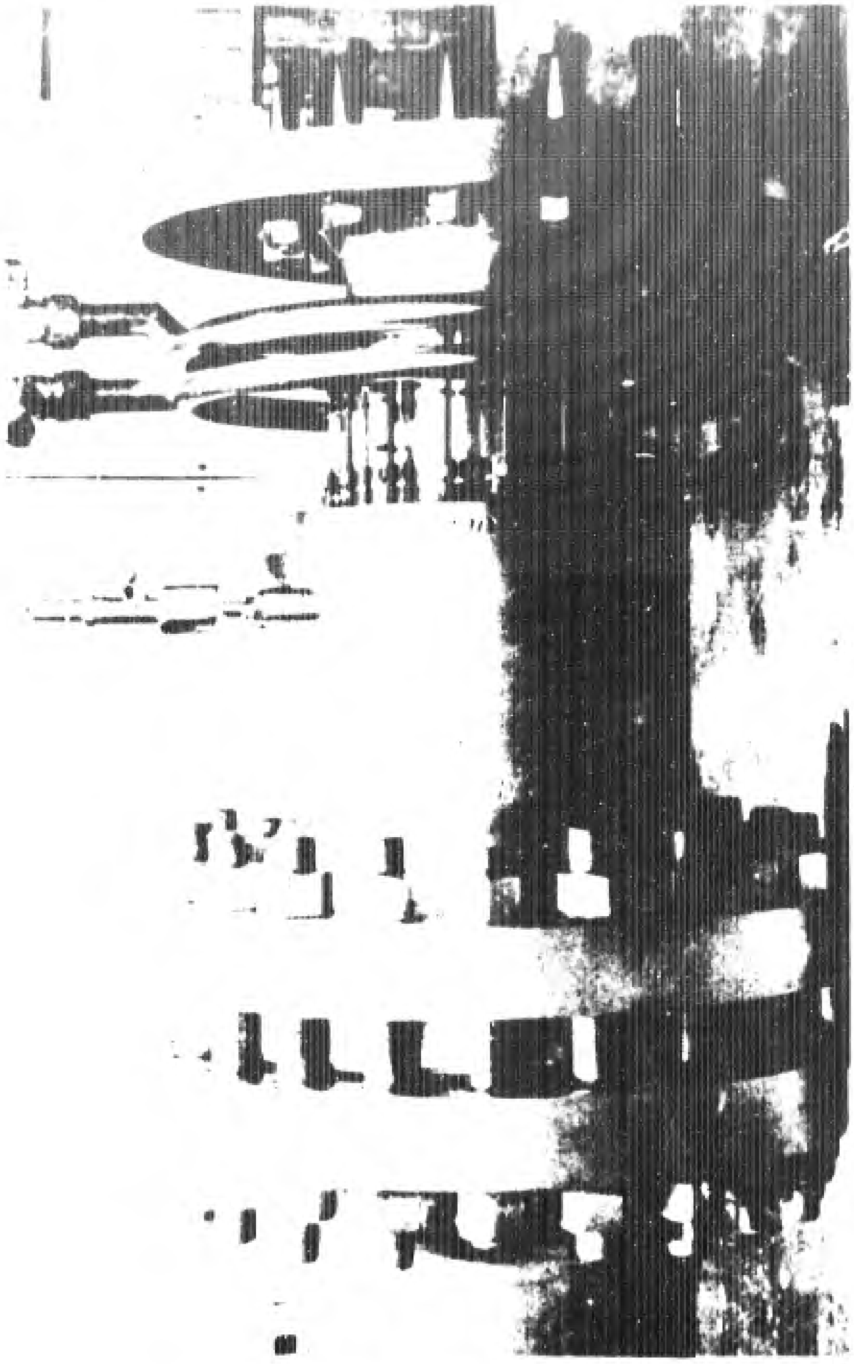
PLUTO MODEL HEATER ASSEMBLY

Figure 7



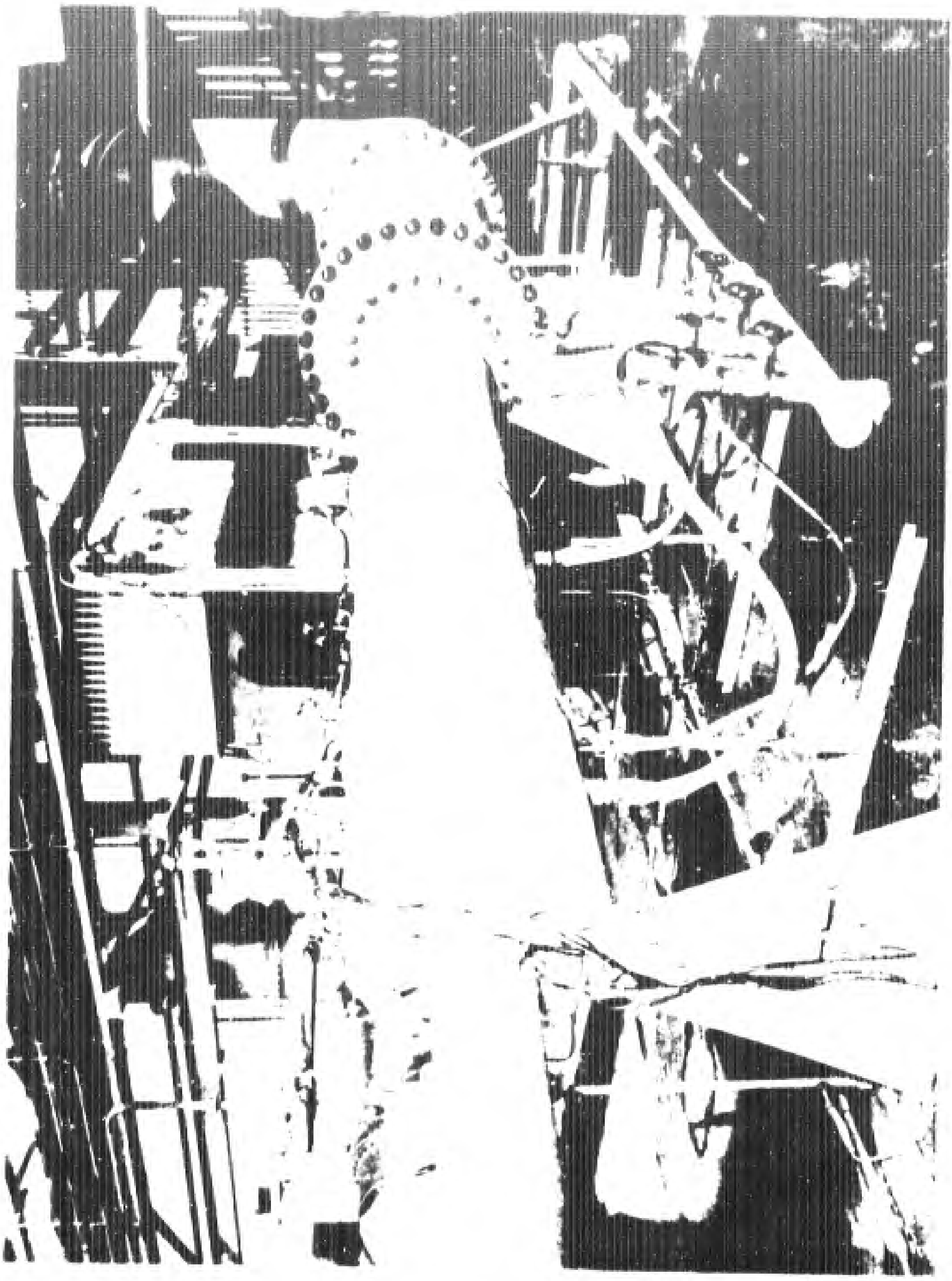
EXHAUST SECTION--PLUTO MODEL HEATER

Figure 8



COMBUSTION CHAMBER--PLUTO MODEL HEATER

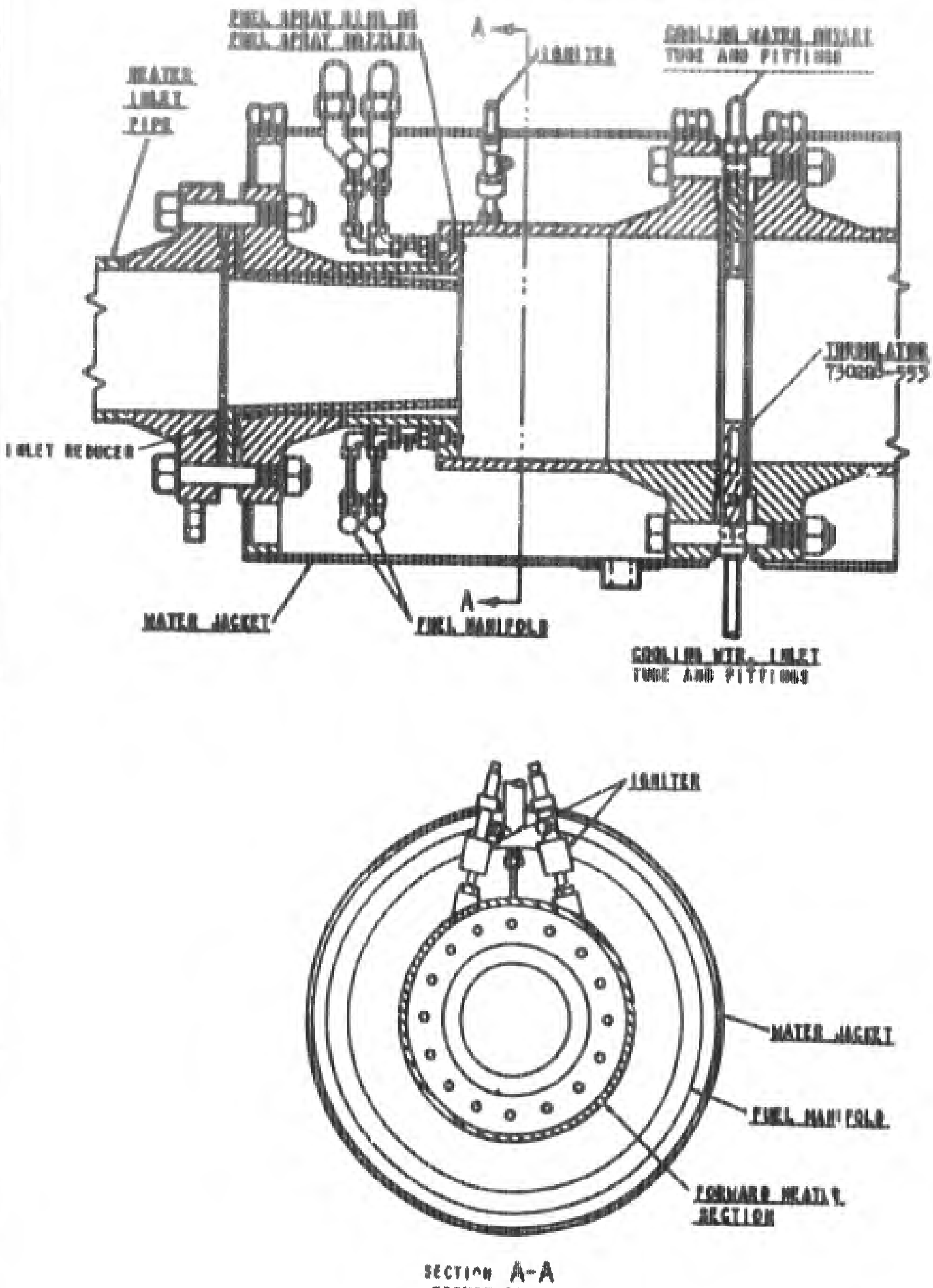
Figure 9



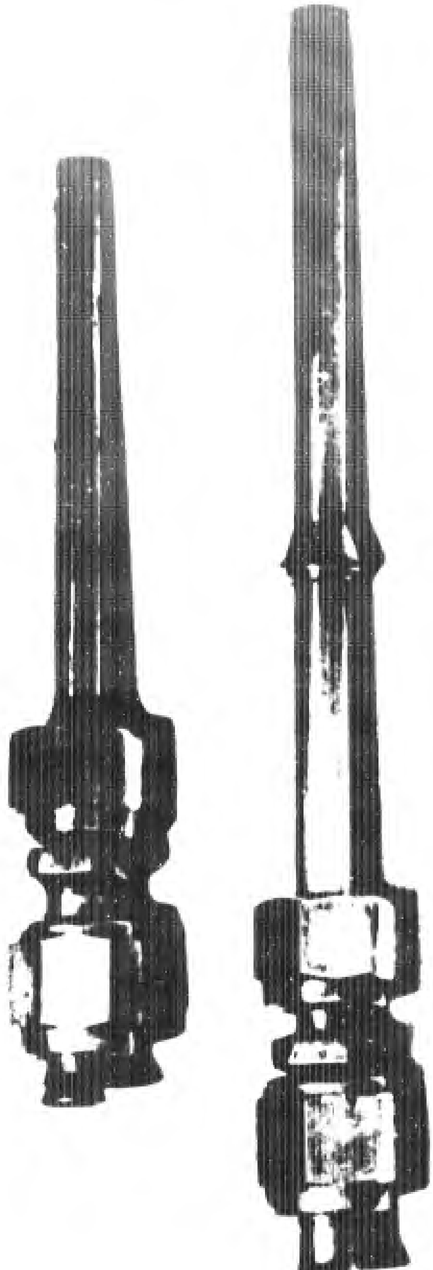
PLUTO MODEL HEATER INSTALLATION

Figure 10

HEATER ASSEMBLY SCALE MODEL HEATER



SECTION A-A
FIGURE 11



60° SLOT NOZZLES--PLUTO MODEL HEATER

Figure 12

90° SLOT NOZZLES--PLUTO MODEL HEATER

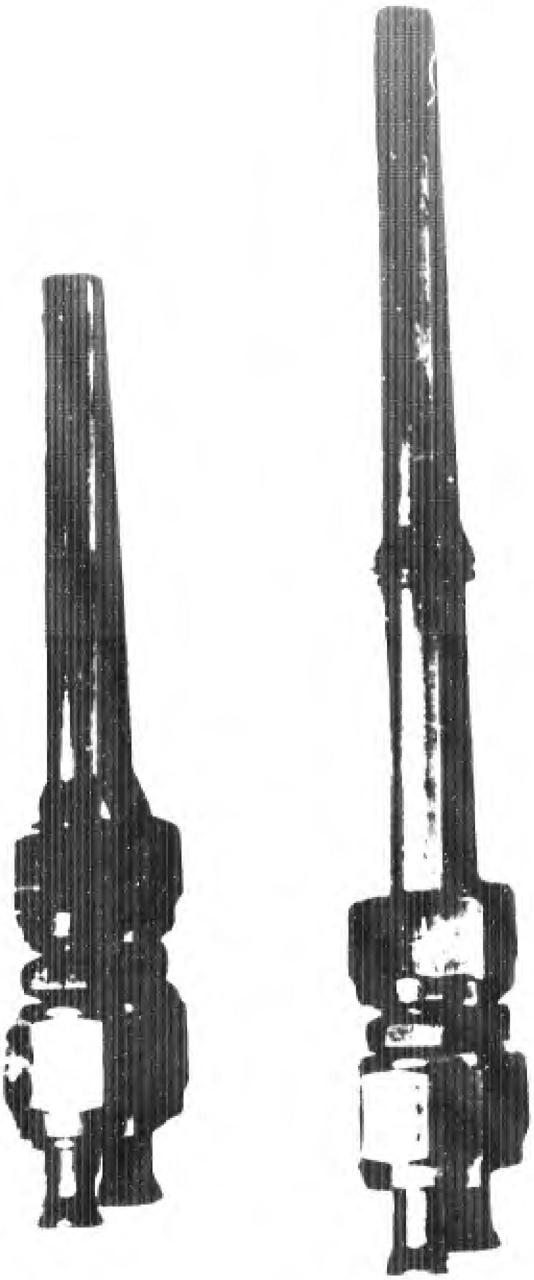
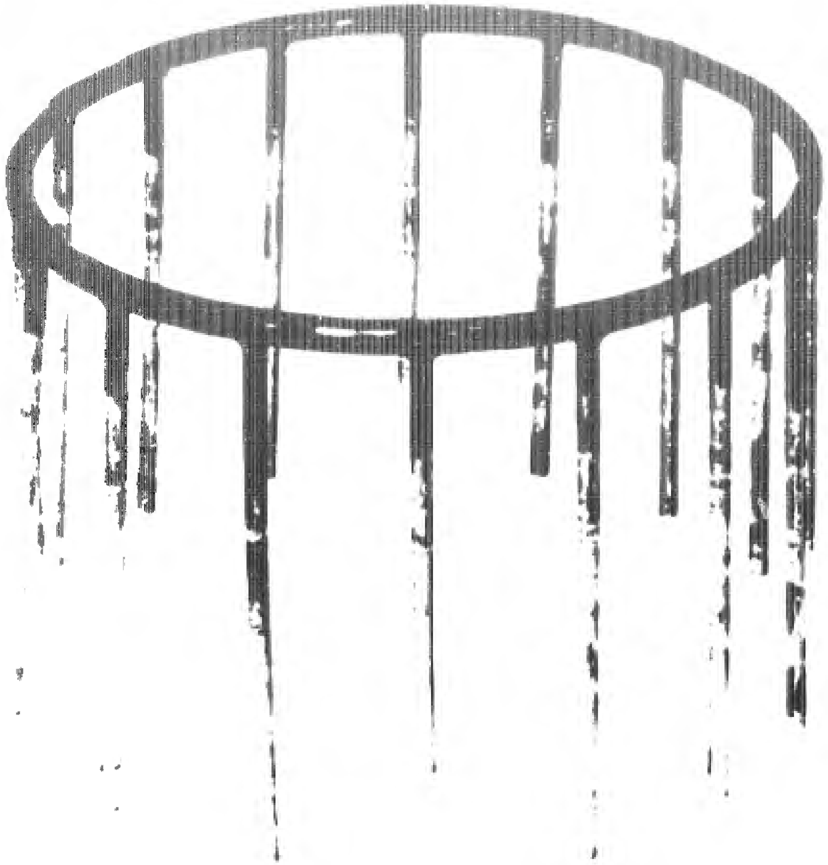


Figure 13



FUEL SPRAY RING--PLUTO MODEL HEATER

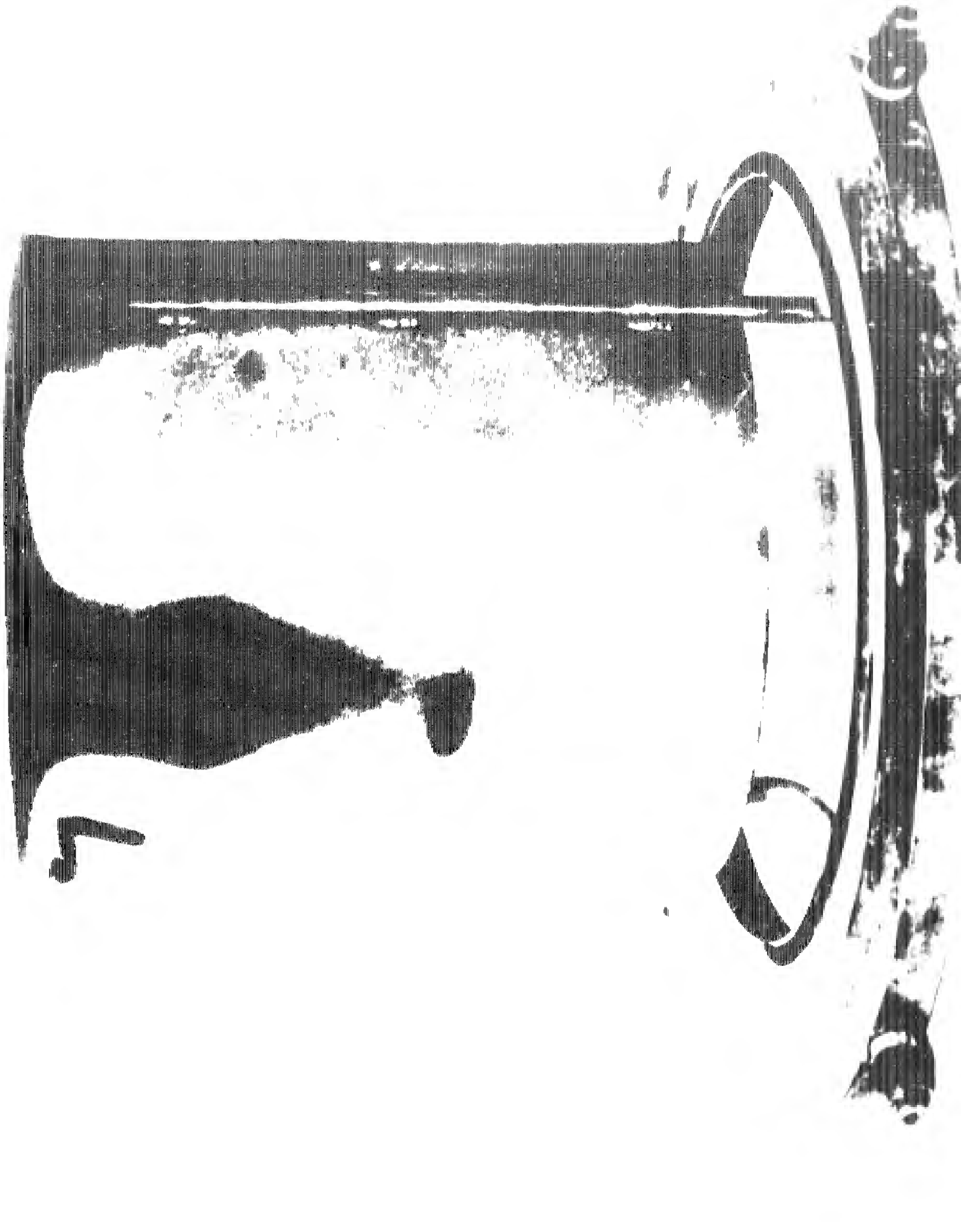
Figure 14

SPLASH PLATE--PLUTO MODEL HEATER

Figure 15

TURBULATOR--PLUTO MODEL HEATER

Figure 16



RECIRCULATOR AFTER TWO RUNS--PLUTO MODEL HEATER

Figure 17

4.0 APPARATUS - continued

4.2 SUE Burner - continued

An inlet reducer was provided so that the burner could be operated at a different inlet-to-combustion-chamber area ratio. The burner ignited and burned stably using the reducer, but the turbulator overheated and melted. Apparently the reducer focused the combustion flame on the turbulator and thereby transmitted more heat to the metal than the cooling water could remove. No data was obtained with this configuration.

Five exhaust orifices were provided to allow evaluation of burner performance at a range of temperatures, flows and pressures. These orifices were inserted between the flange faces of the fourth and fifth spool sections. A typical exhaust orifice is shown in Figure 18.

4.3 Instrumentation

The burner was instrumented to measure the following parameters: air flow, fuel flow, inlet air temperature and pressure, exhaust gas temperature, and exhaust gas pressure.

Air flow was measured with an ASME sharp-edged orifice in the air supply line. Pressure upstream of the orifice and orifice ΔP were displayed on a photo panel in the control shed.

Fuel flow was measured with turbine type flow meters upstream of the flow control valve. The flow was indicated as % of maximum on a gage on the photo panel.

Inlet air total temperature was measured with an iron-constant thermocouple probe. This temperature was displayed on a "Lewis" direct reading temperature gage on the photo panel. Inlet total pressure was measured with two probes manifolded together and connected to a pressure gage on the photo panel. The pressures and temperatures were measured in the same vertical plane.

TYPICAL EXHAUST ORIFICE PLUTO MODEL HEATER

Figure 18

4.0 APPARATUS - continued

4.3 Instrumentation - continued

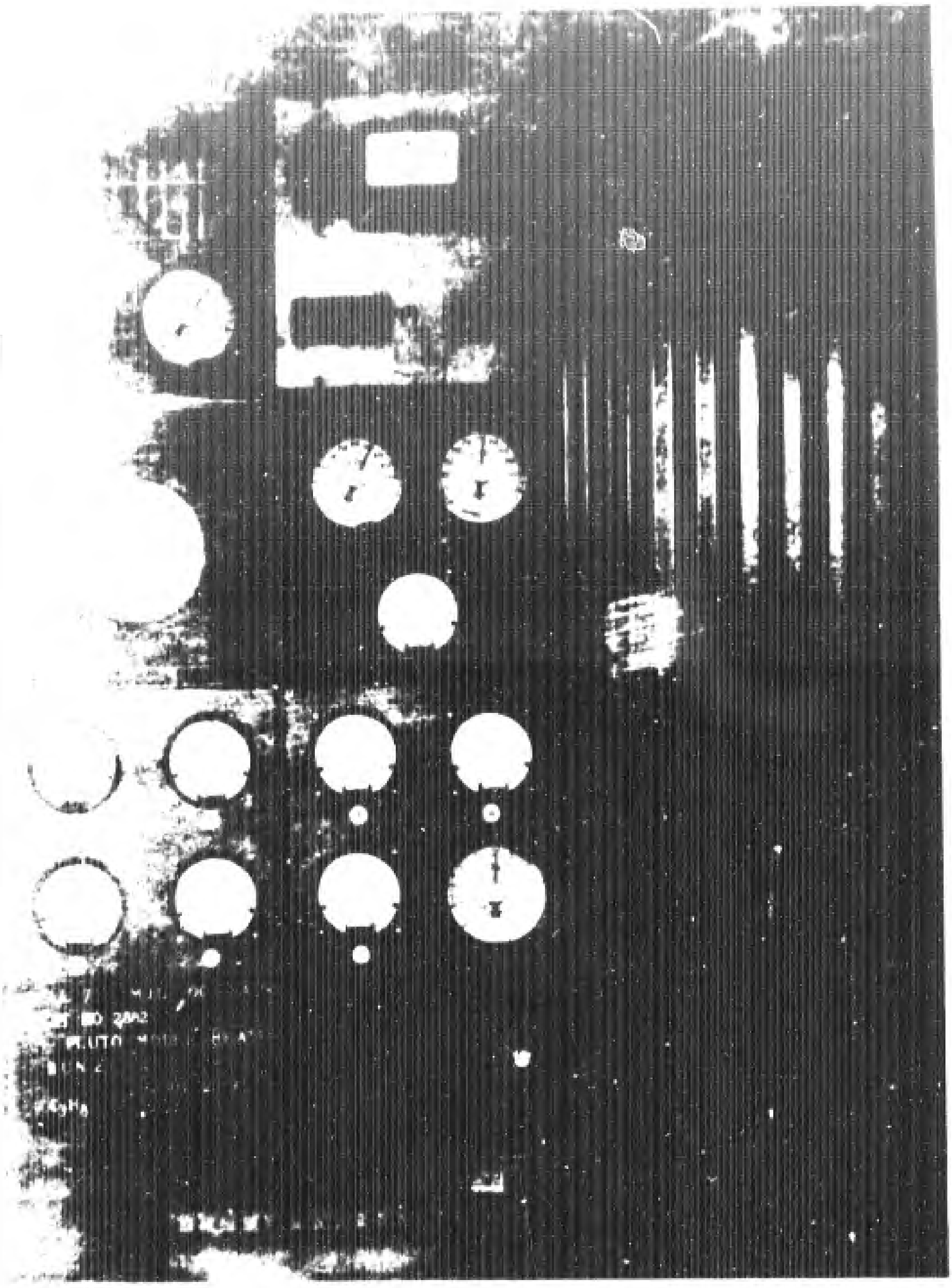
Exhaust gas temperature was measured at seven points across the diameter of the burner with an equal area rake. Chromel-alumel thermocouples were used as sensing elements. The temperatures were displayed on "Lewis" direct reading temperature gages on the photo panel.

Exhaust gas total pressure was measured with a total pressure rake located in the same vertical plane as the temperature probe. This pressure was indicated on a gage located on the photo panel.

Combustion chamber wall temperatures were measured at four points along the length of the chamber. These measurements were used for control purposes only. The data obtained from these readings was not used to evaluate burner performance.

Cooling water temperature was measured with one thermocouple at the supply point to the burner and a separate couple at each cooled section to measure the discharge water temperature. The flowrate of water to each section was also measured.

A photograph of the photo panel record of a test run is shown in Figure 19.



RUN NO. [illegible]

Figure 19

5.0 DISCUSSION OF RESULTS

5.1 The various burner configurations tested were evaluated on the basis of combustion efficiency and temperature profile in the exhaust gas. The combustion efficiency as used here is defined as the ratio of actual gas temperature rise to ideal temperature rise. The actual temperature rise was determined by adding the gas temperature loss, due to heat lost through the water cooled walls to the measured gas temperature rise through the burner. The ideal temperature rise is the rise which would occur if the fuel was completely burned to CO_2 and H_2O. The temperature profile in the exhaust gas was measured directly with the temperature rake.

Combustion efficiency is plotted vs. a modified Dezubay number, $\frac{V}{DP}$, where V is the gas velocity through the burner in ft/sec, D is the exit blockage ratio (burner flow area minus exit orifice area divided by burner flow area $\left(\frac{A_B - A_o}{A_B}\right)$, and P is the absolute pressure in the burner in psia. Efficiency data is summarized in Figure 1.

5.2 The recirculator evaluation tests were terminated after two runs because of inadequate cooling of the recirculator. The first run was made at low flow and the cooling problem was not apparent. The second run was made at high flow and the recirculator overheated. The data obtained from the second run showed that there is no particular advantage in using the recirculator since combustion efficiency for this test was 75%.

5.3 Final analysis of the fuel injector evaluation tests indicated that the best combustion efficiency was obtained with the 60° slot nozzles. A comparison of the efficiencies and temperature profiles for each fuel injector using one turbulator in the upstream position is shown in Figures 20, 21, 22 and 23. From the data, it can be seen that there is not a large difference in efficiency between the 60° and 90° slot nozzles. The slight improvement with the 60° nozzles is explained by the fact that the fuel is not forced into the high velocity core

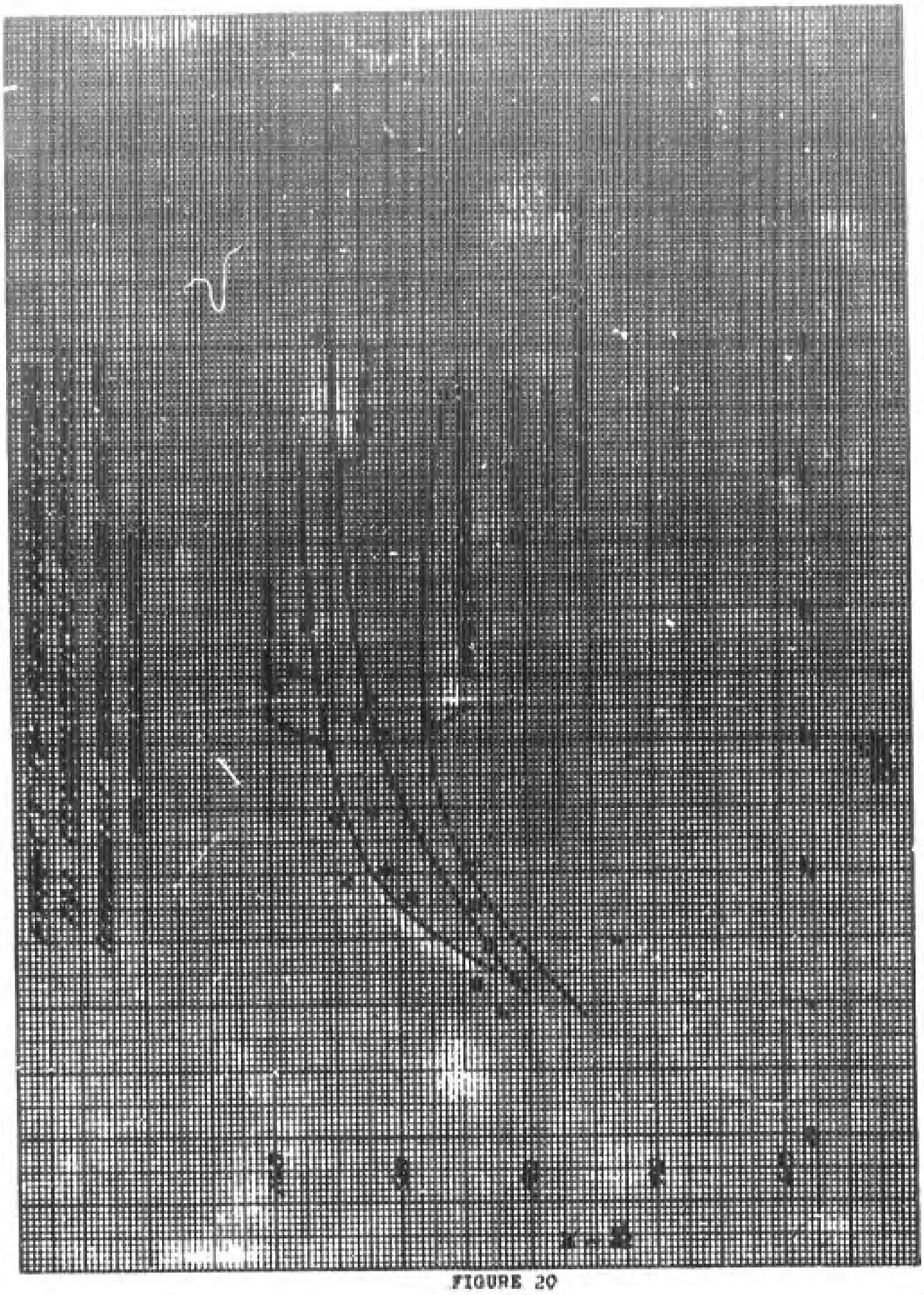


FIGURE 20

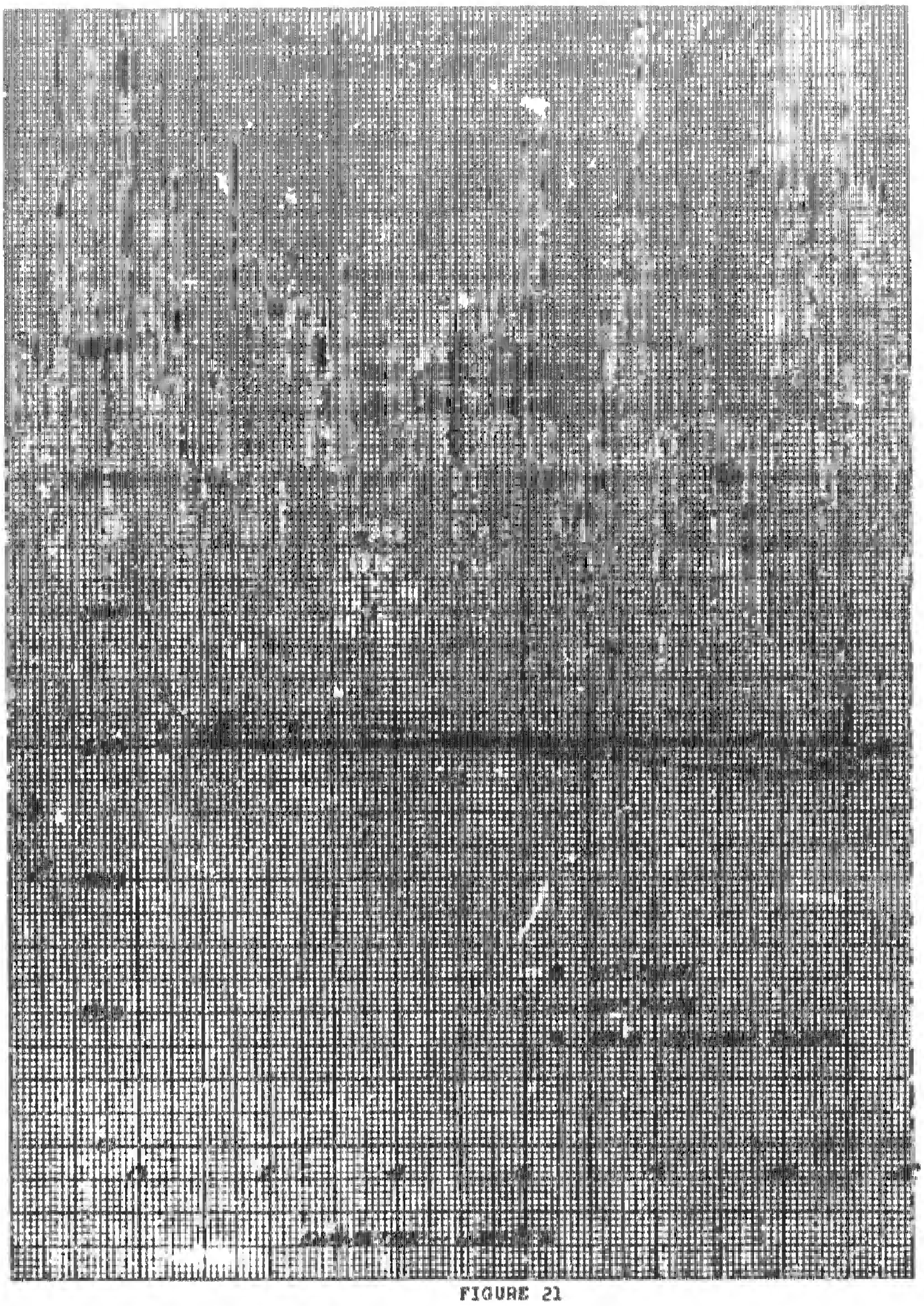


FIGURE 21

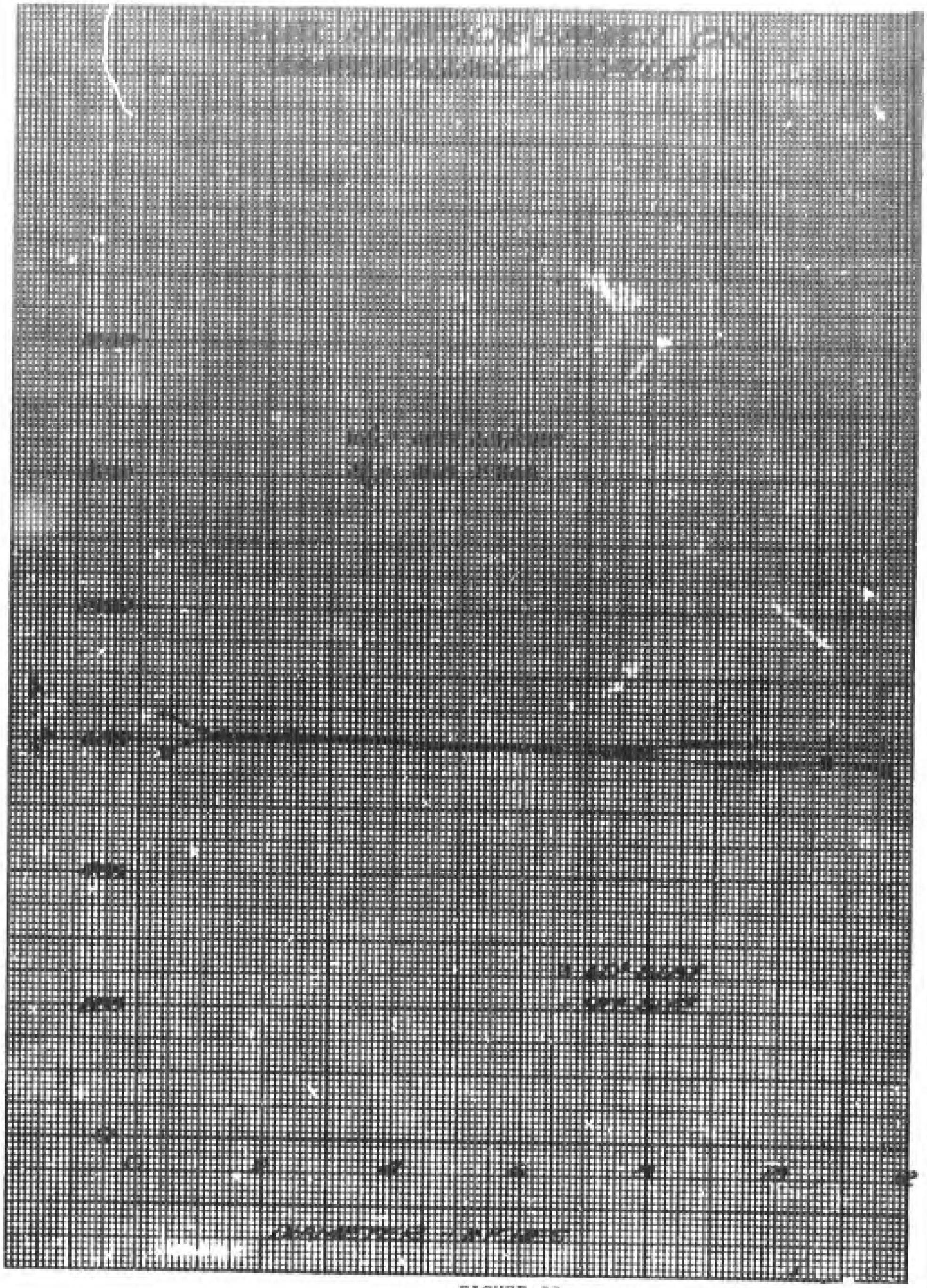


FIGURE 22

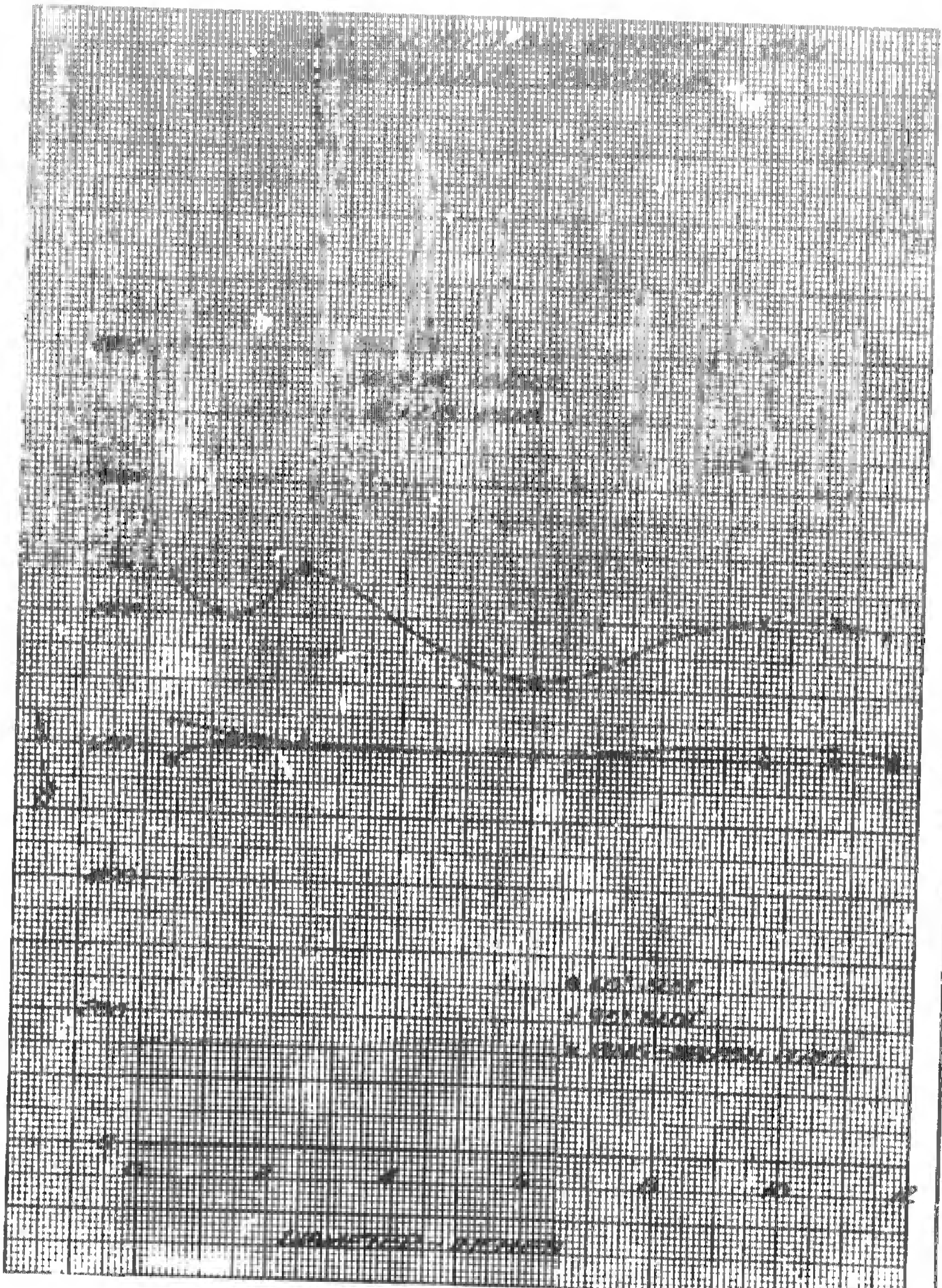


FIGURE 23

5.0 DISCUSSION OF RESULTS - continued

5.3 continued

of air entering the burner as much as with the 90° slot nozzles. This allows more of the fuel to remain in the recirculation zone behind the step where it can burn more completely. The poor performance of the ring and splash plate is explained by the fact that the fuel is injected directly into a high velocity stream and is carried downstream before it can burn completely.

5.4 The turbulator evaluation tests indicated that higher combustion efficiencies were obtained with one turbulator in the upstream position. A comparison of combustion efficiency and temperature profiles in the exhaust gas for each turbulator location is shown in Figures 24, 25, 26, 27, and 28. The simultaneous use of two turbulators produced a very high pressure drop, and yielded the same efficiency as that obtained with just one turbulator.

The increase in combustion efficiency with one turbulator in the upstream position can be explained by the fact that the turbulator creates a large turbulent low velocity area in the annulus upstream of the turbulator face. This low velocity zone, plus the low velocity zone at the step, provide a larger volume in which combustion can take place. The overall effect is to increase the fuel stay time in the combustion chamber, thereby permitting complete combustion.

5.5 The performance documentation runs were made to demonstrate the heater performance over the entire envelope of pressure and temperature indicated by the PLUTO testing requirements. The test points were chosen to simulate the gas velocity, temperature and pressure, which the full scale heater would experience. These test points are listed in TABLE 1. The configuration used in these tests consisted of one turbulator in the upstream position and the 90° slot nozzles. The 90° slot nozzles were chosen after a preliminary survey of the data, subsequent data shows that the 60° slot nozzles give slightly better combustion efficiency.

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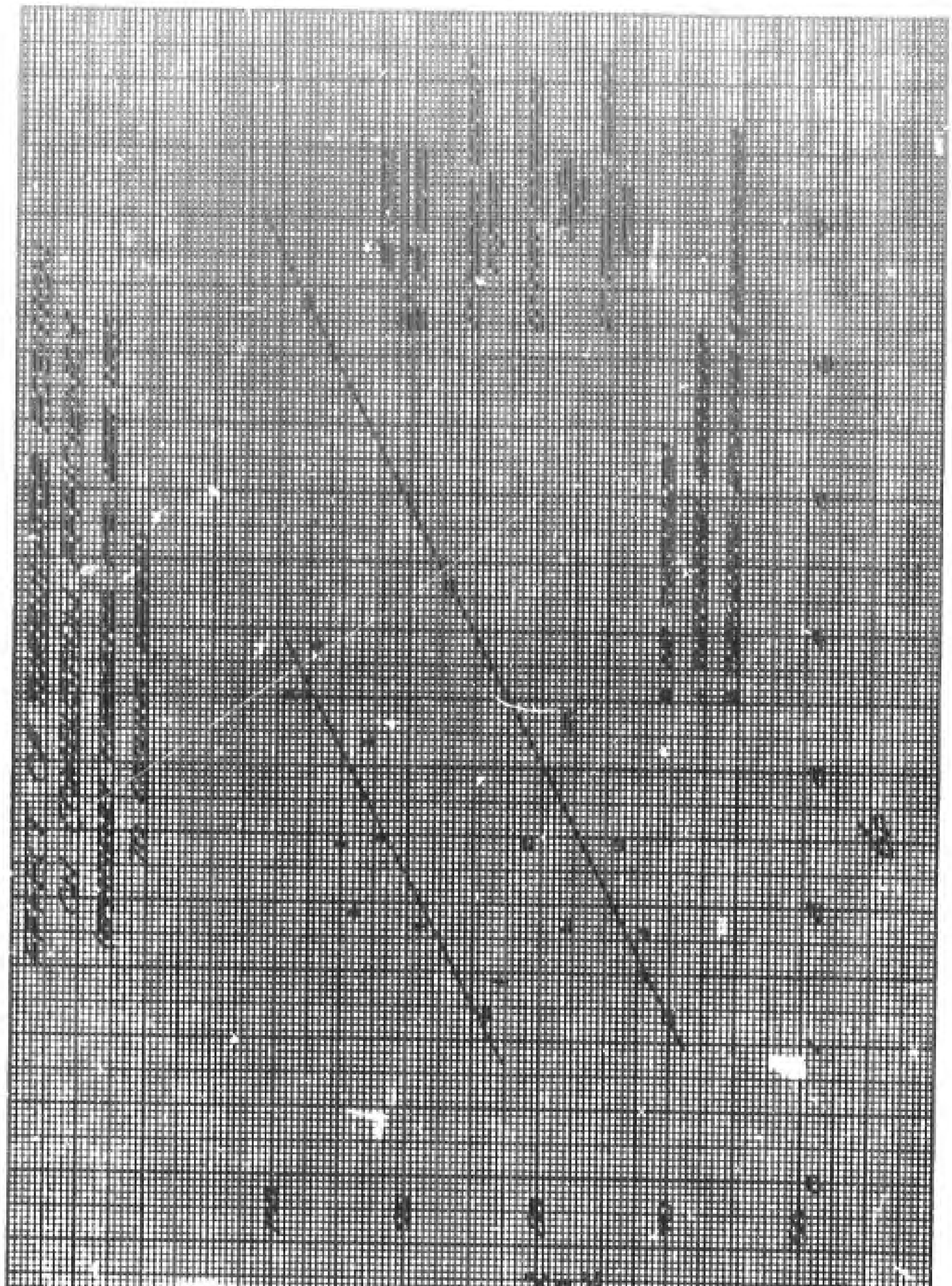

FIGURE 24

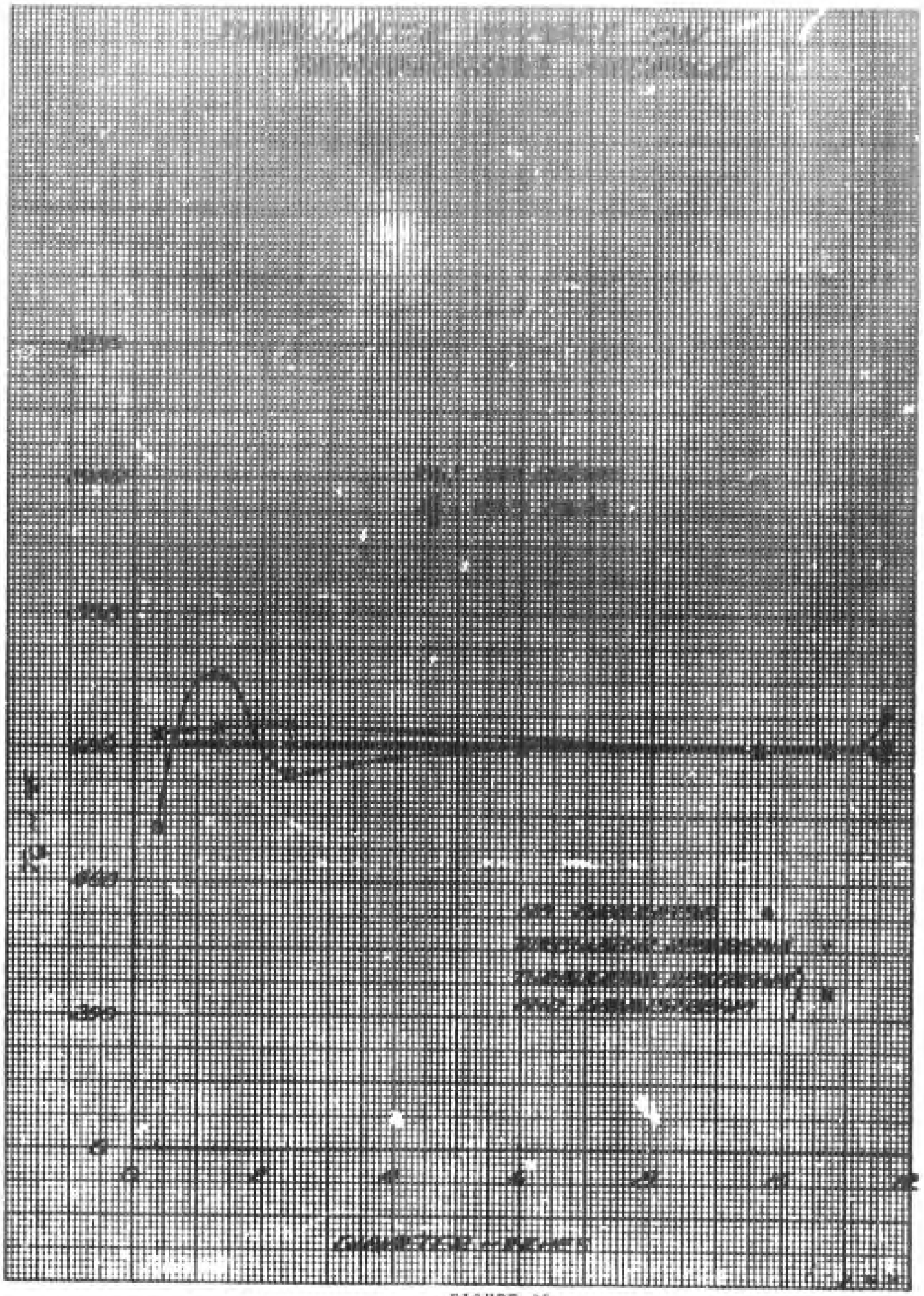

FIGURE 25

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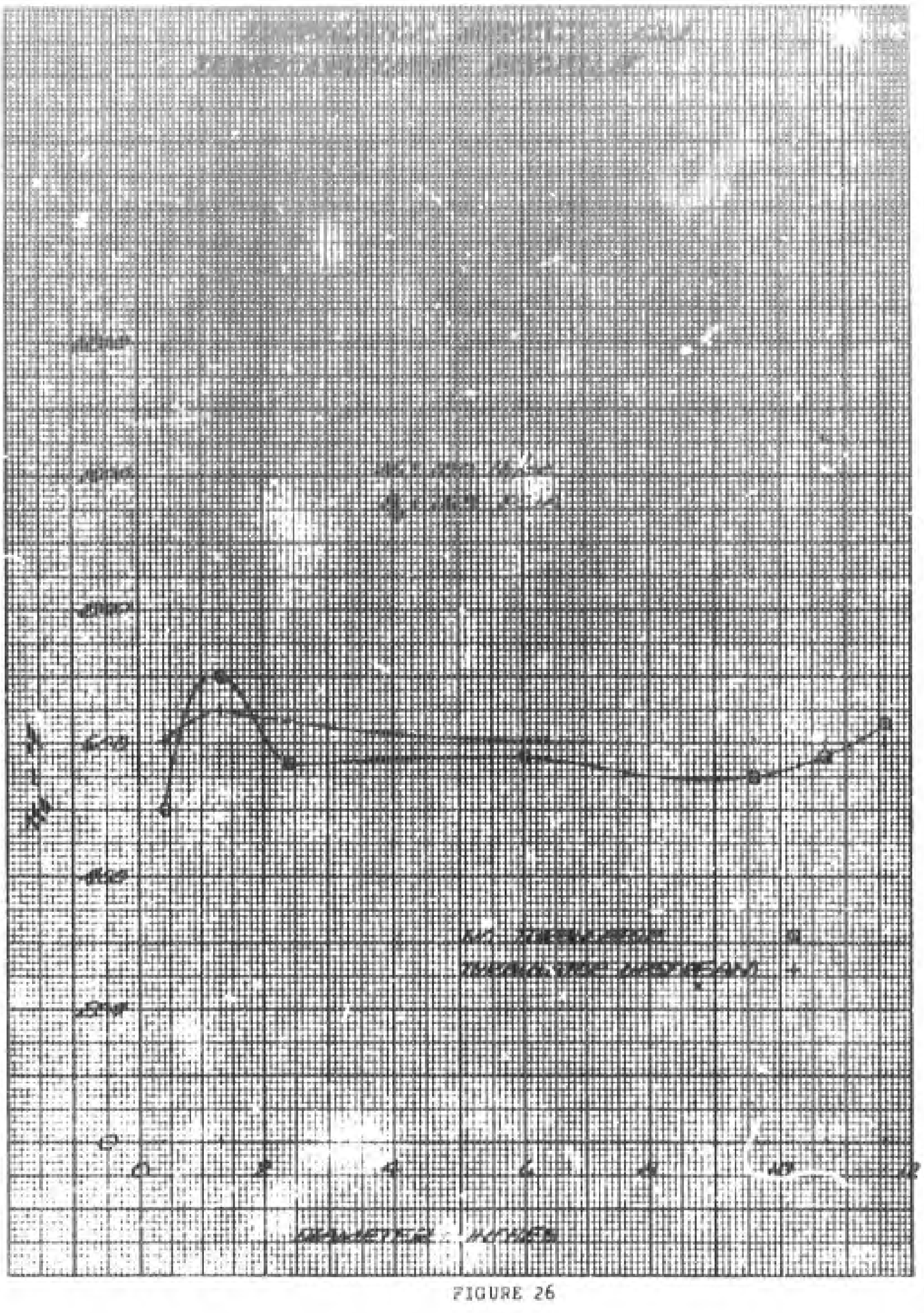

FIGURE 26

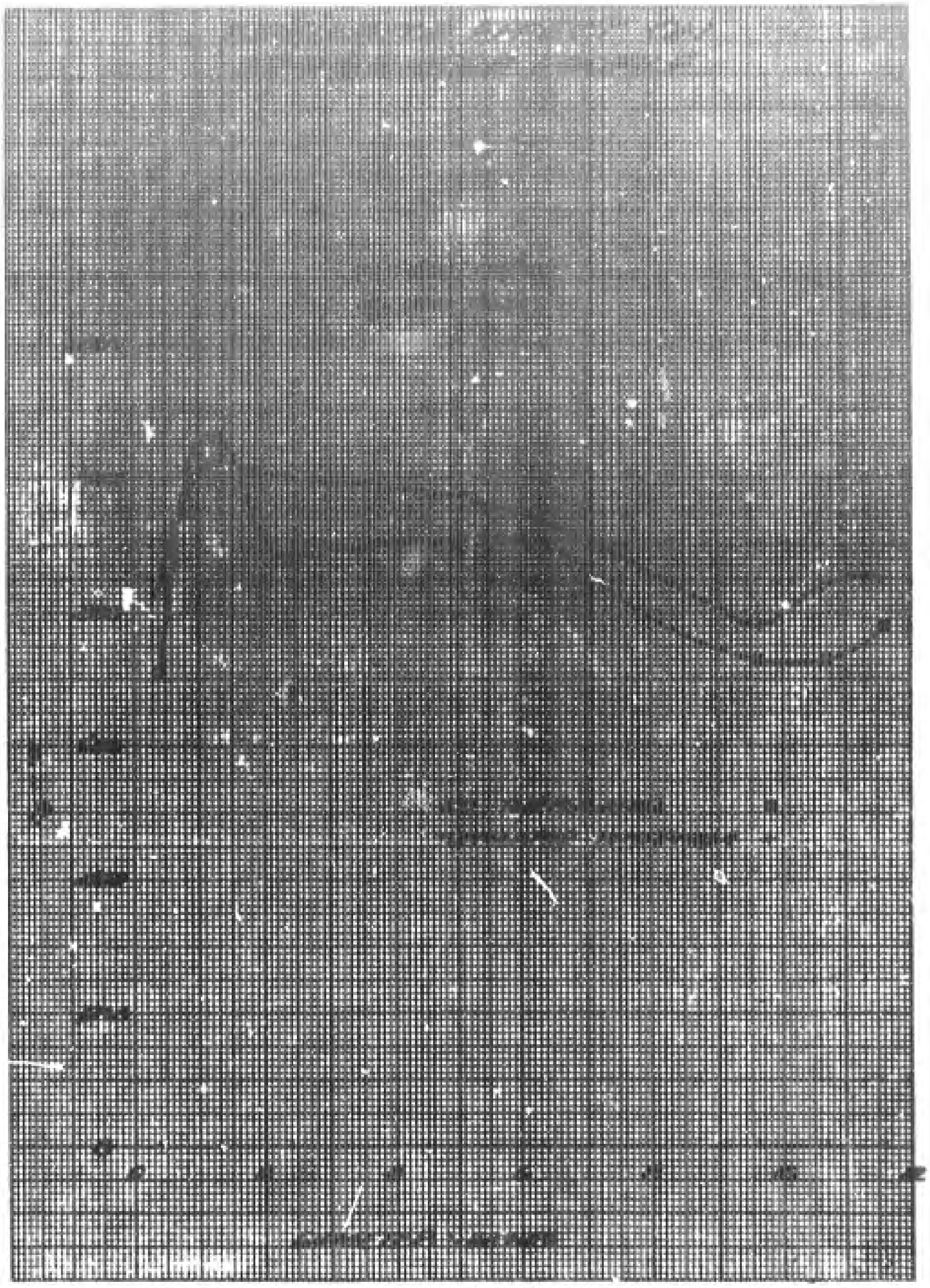

FIGURE 27

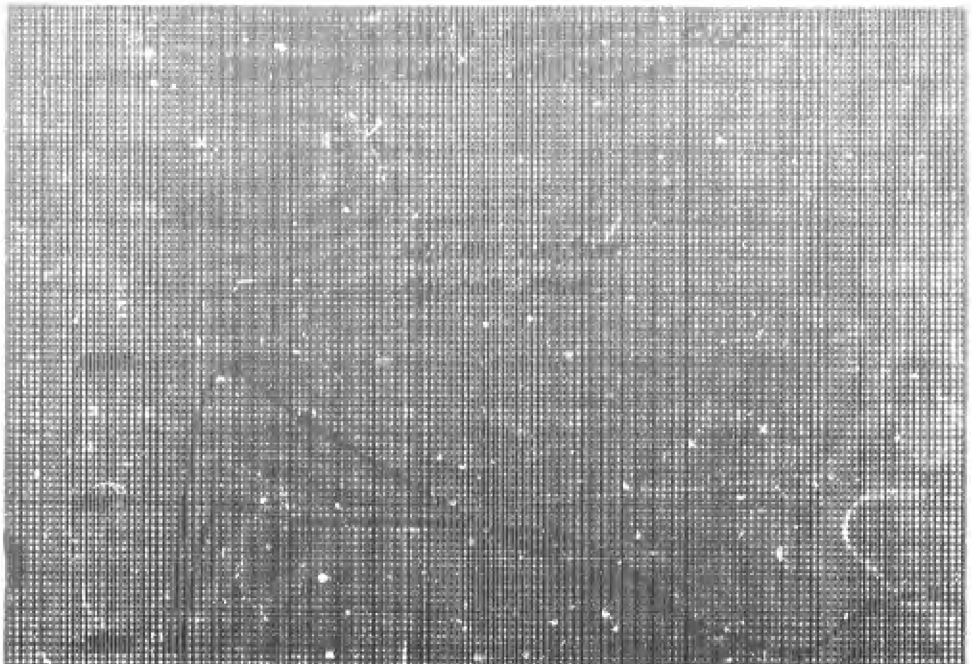

FIGURE 28

5.0 DISCUSSION OF RESULTS - continued

5.5 continued

The combustion efficiency and temperature profiles for the documentation runs are shown in Figures 1, 2, and 29 - 33. The efficiency on all runs show a definite trend to increase to a maximum of 95-100% at $\frac{V}{DP}$ = 4 to 5 and then decrease.

5.6 A sample of exhaust gas was analyzed for relative concentrations of CO_2, CO, N_2, H_2O, and unburned fuel. The analysis showed no CO, indicating that the combustion of the percentage of the fuel which was burned was complete. A small amount of unburned fuel was found in the sample (0.24% by volume on one test run). This amount of unburned fuel corresponds to a combustion efficiency of 84.3% for this run and agrees with the efficiency calculated from test data (84%).

5.7 A series of four runs were made using 80-octane gasoline instead of liquid propane. These runs, when compared with liquid propane runs, show the effects of each fuel on combustion efficiency and temperature profile. These parameters are compared for both fuels in Figures 34, 35, and 36. After the 80-octane gasoline runs, a deposit of soft carbon was noted on the inside of the heater This indicates incomplete combustion of the fuel. No carbon deposits were noted after any of the liquid propane runs. The presence of carbon would disqualify this fuel for use even though the combustion efficiency is as good as that obtained with liquid propane. Samples of the combustion products from the 80-octane runs were analyzed to determine relative concentrations of CO_2, CO, N_2, O_2, H_2O, and unburned hydrocarbons. The results of these analyses showed no CO, and some unburned hydrocarbons, in addition to the gaseous constituents. The lack of CO shows that the fuel which burned did so completely (to CO_2 and H_2O). The rest of the fuel either passed through the heater unburned or was decomposed to free carbon and hydrogen. The decomposition of some of the fuel is indicated by the carbon deposits found in the heater after the 80-octane runs.

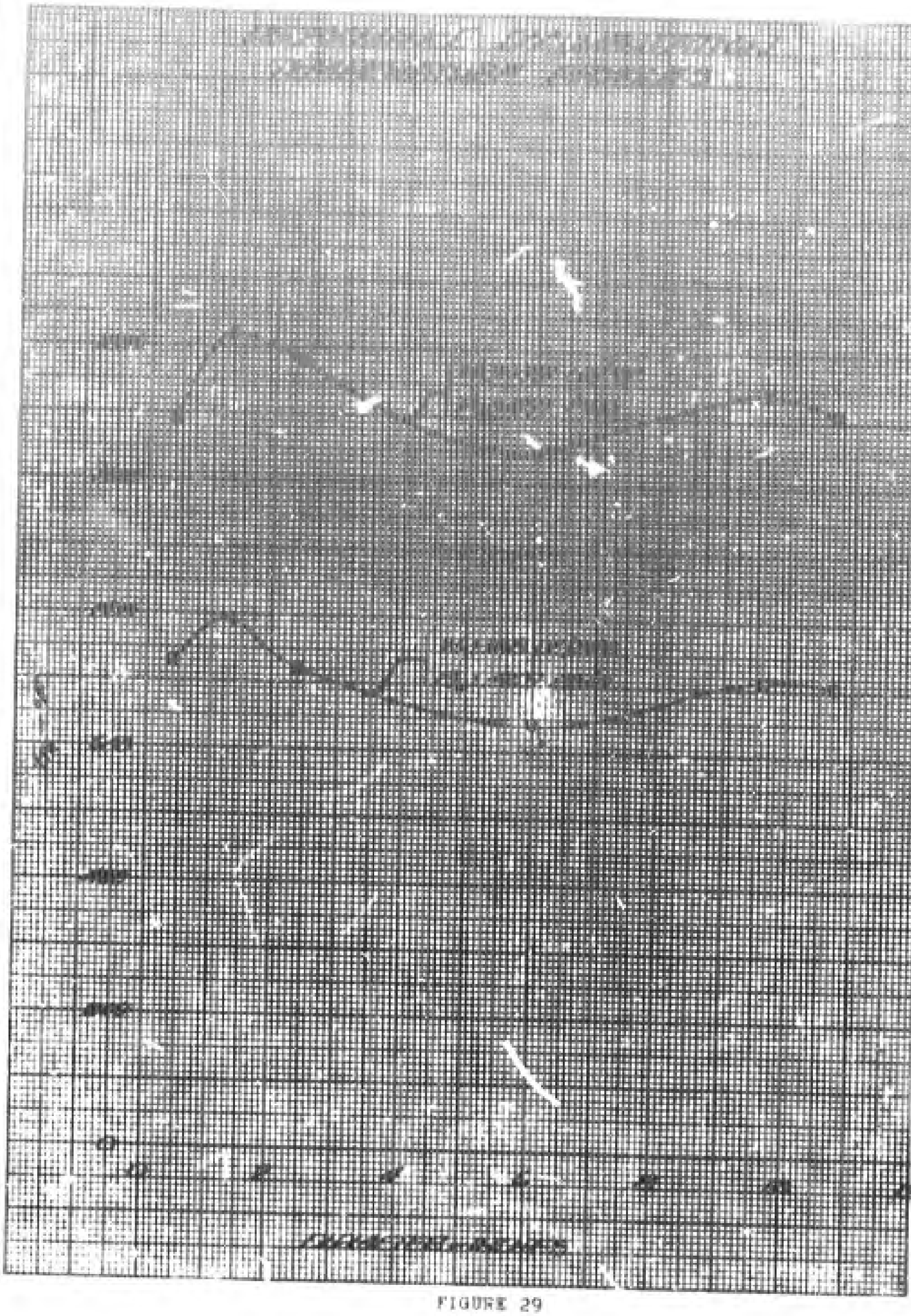

FIGURE 29

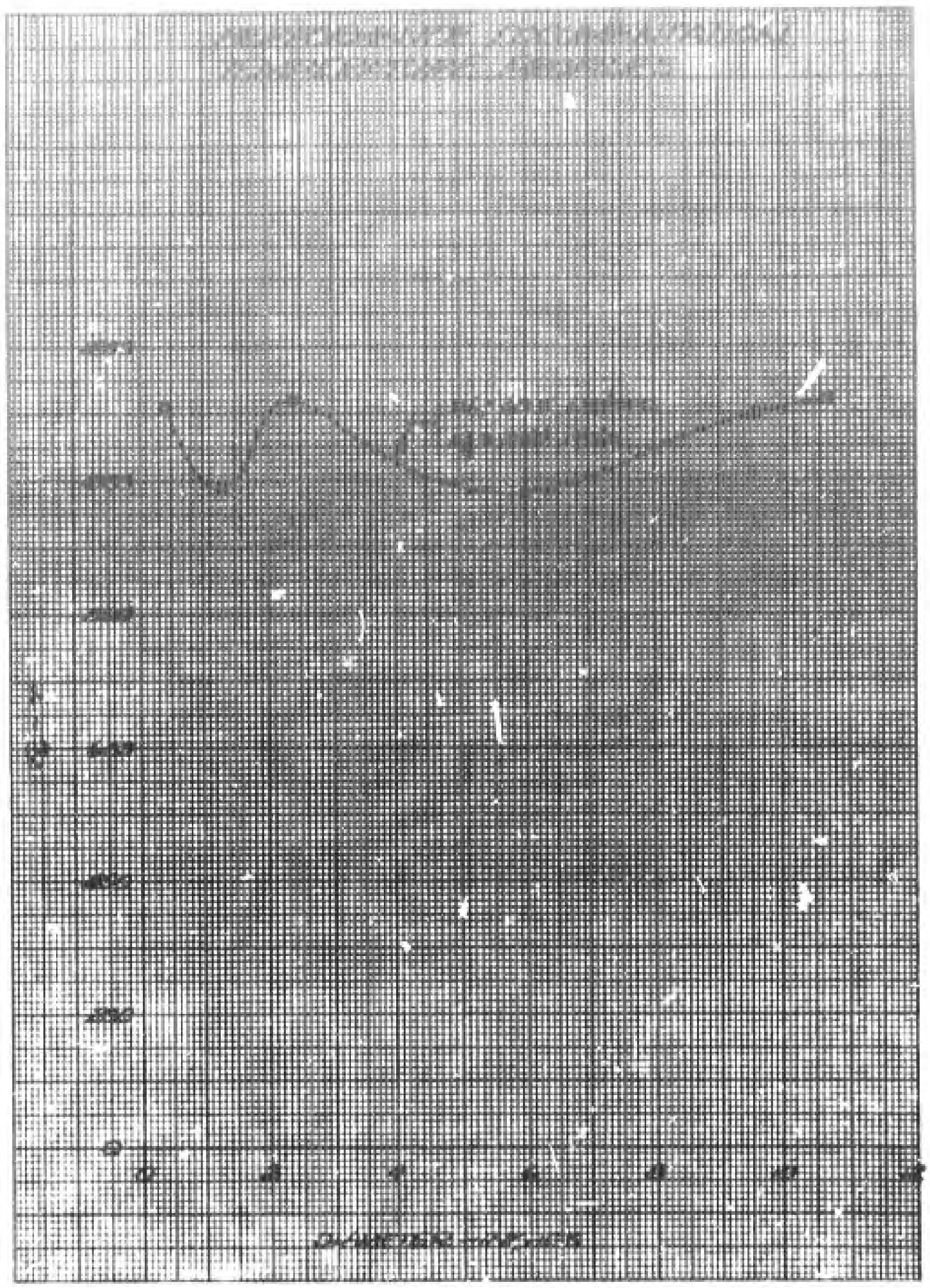

FIGURE 30

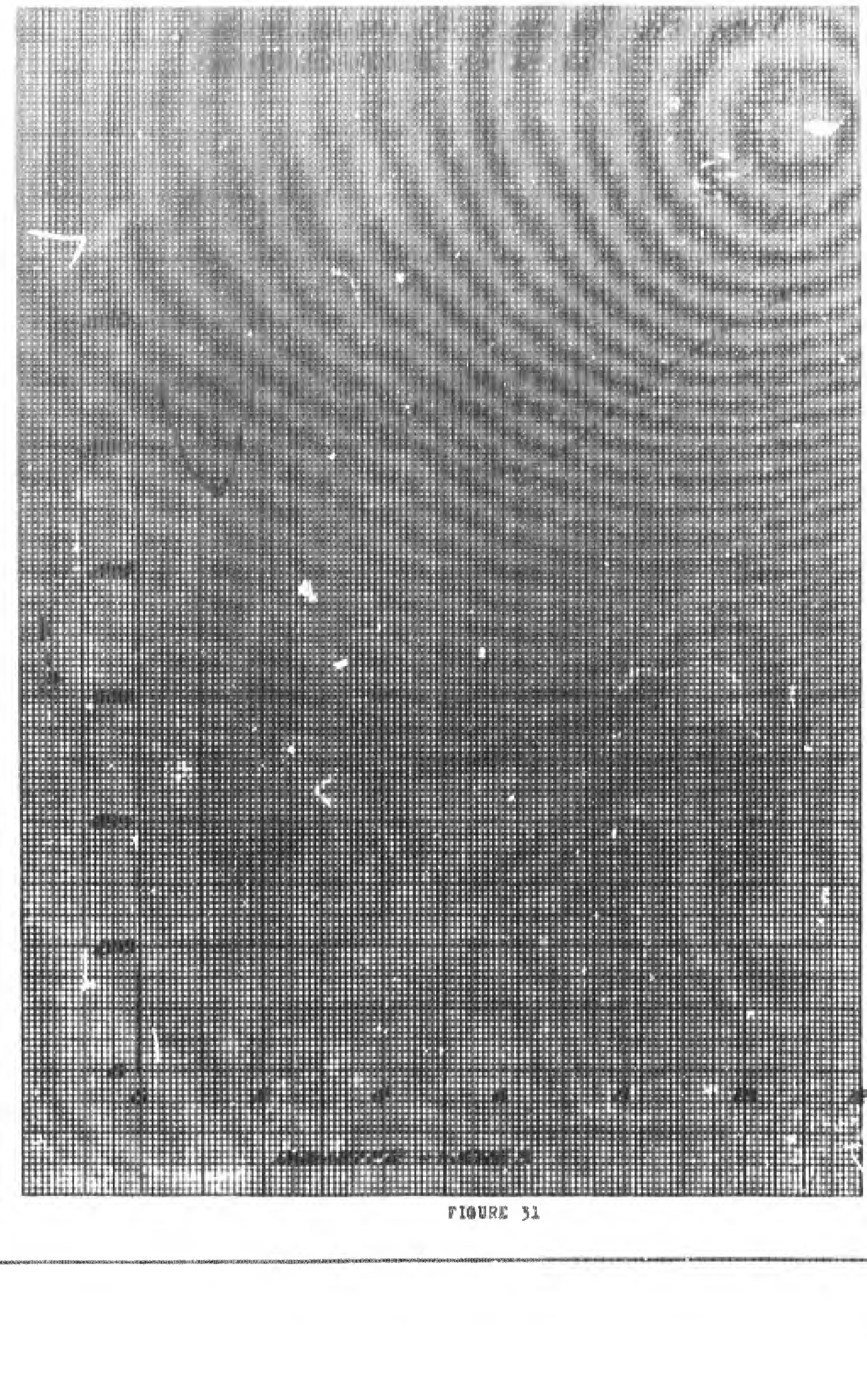

FIGURE 31

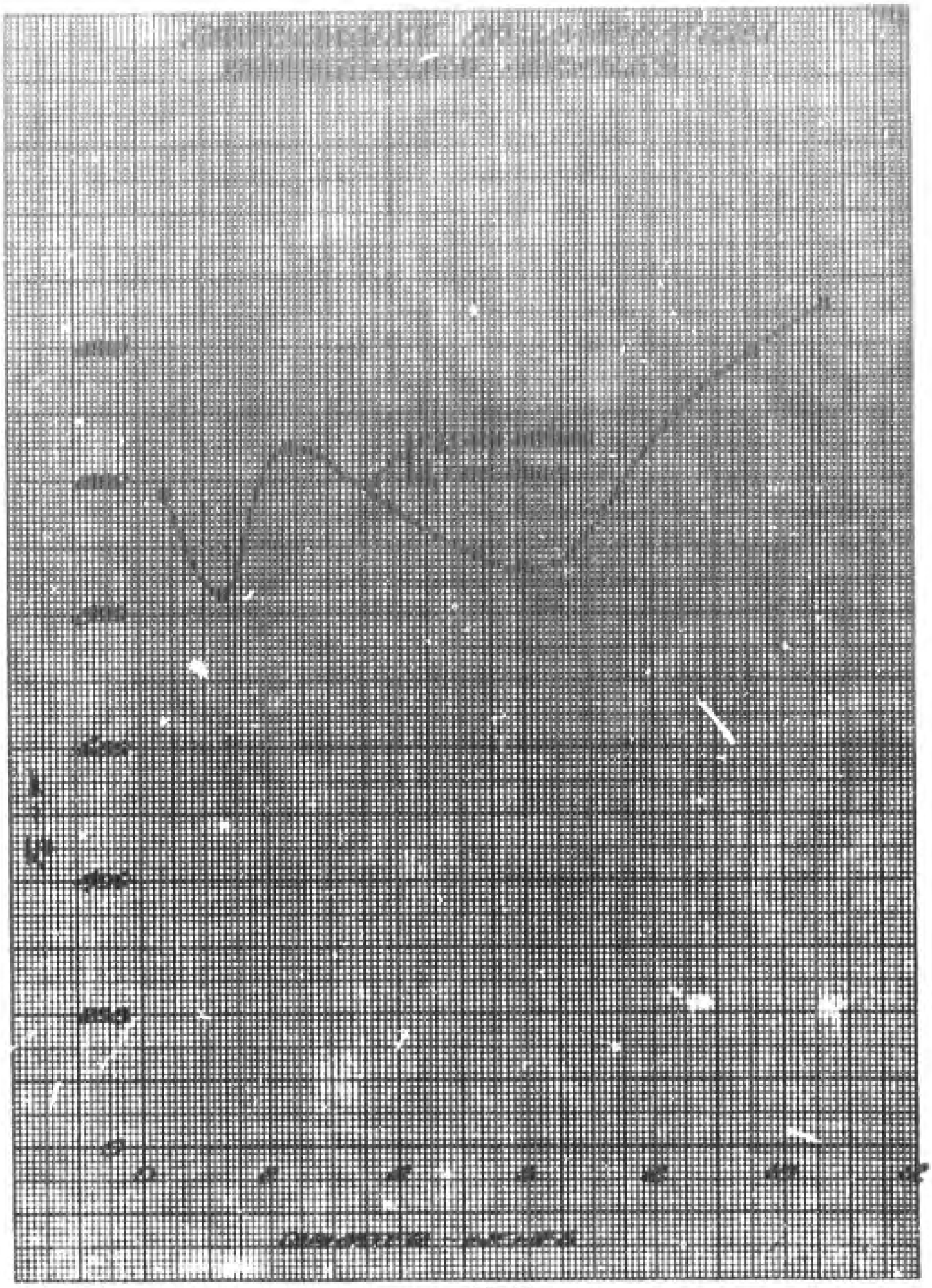

FIGURE 32

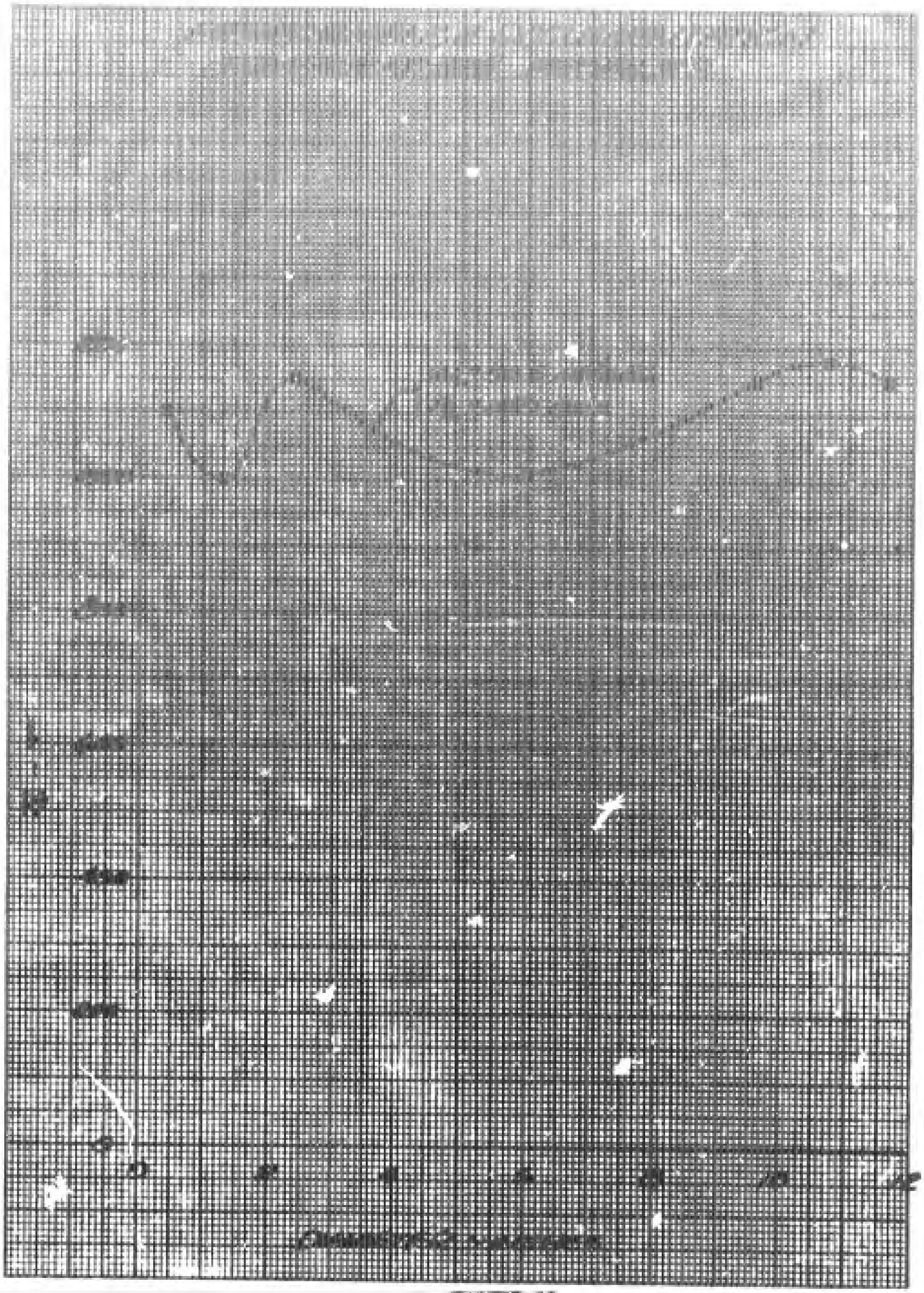

FIGURE 33

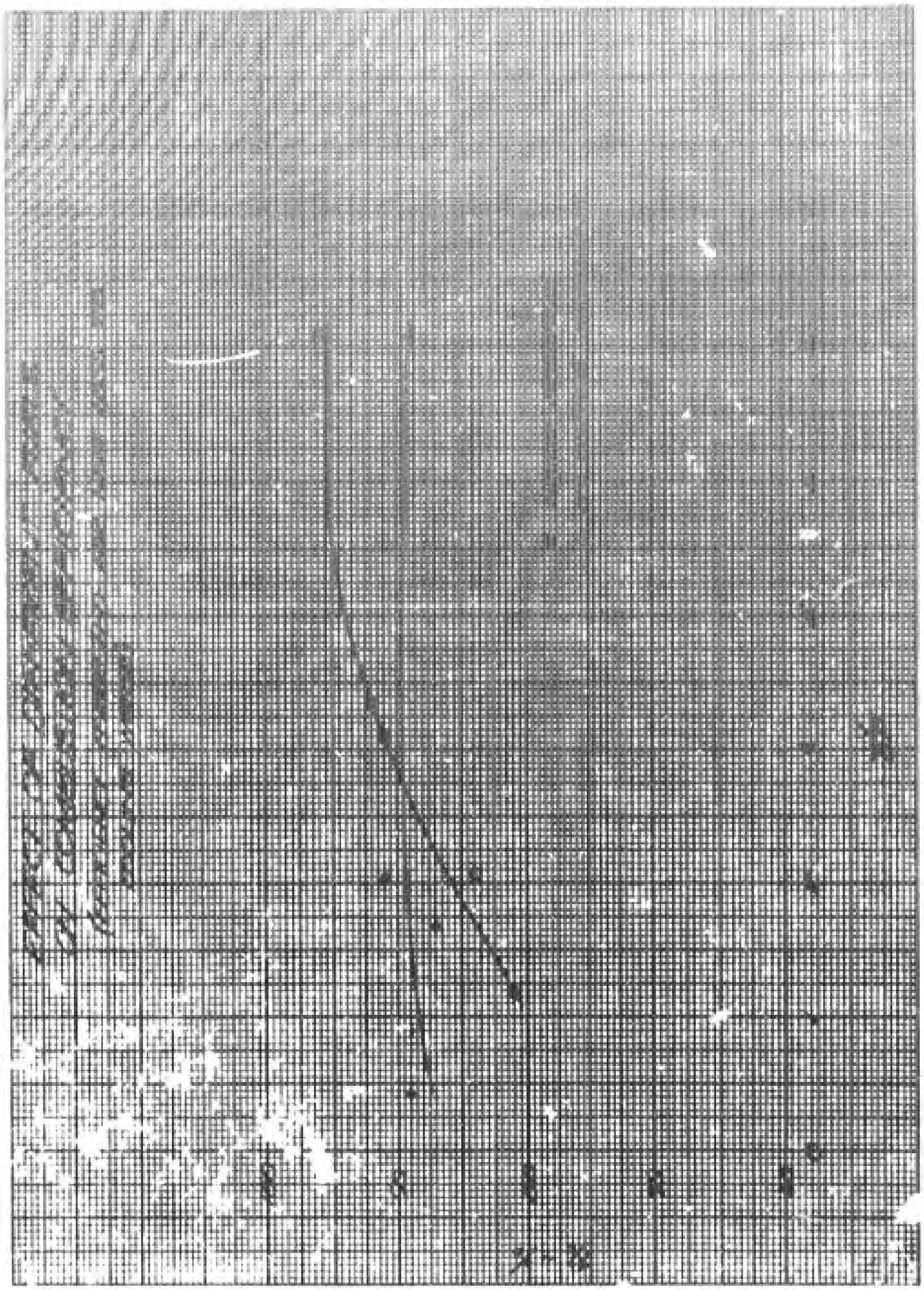

FIGURE 34

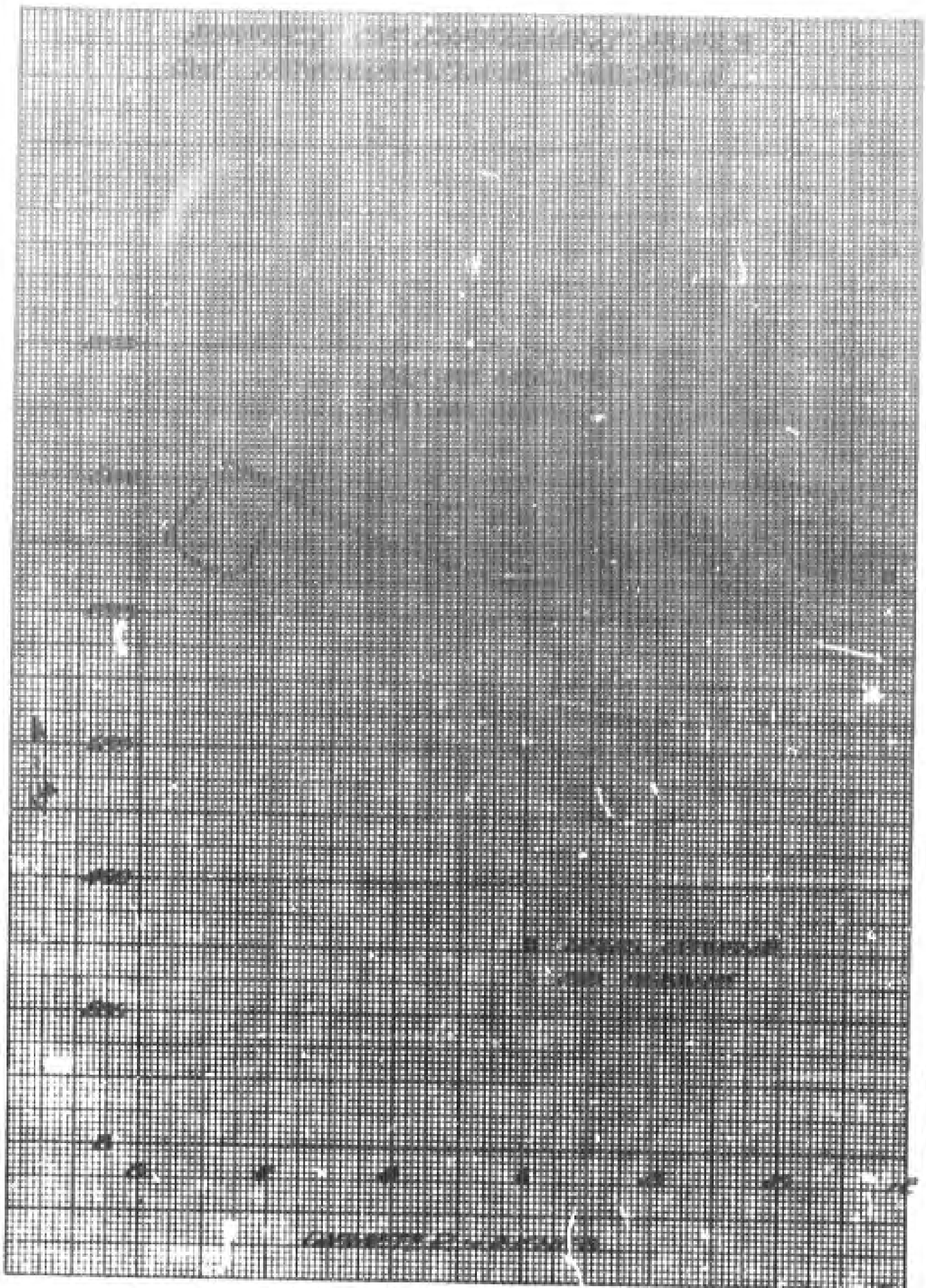

FIGURE 35

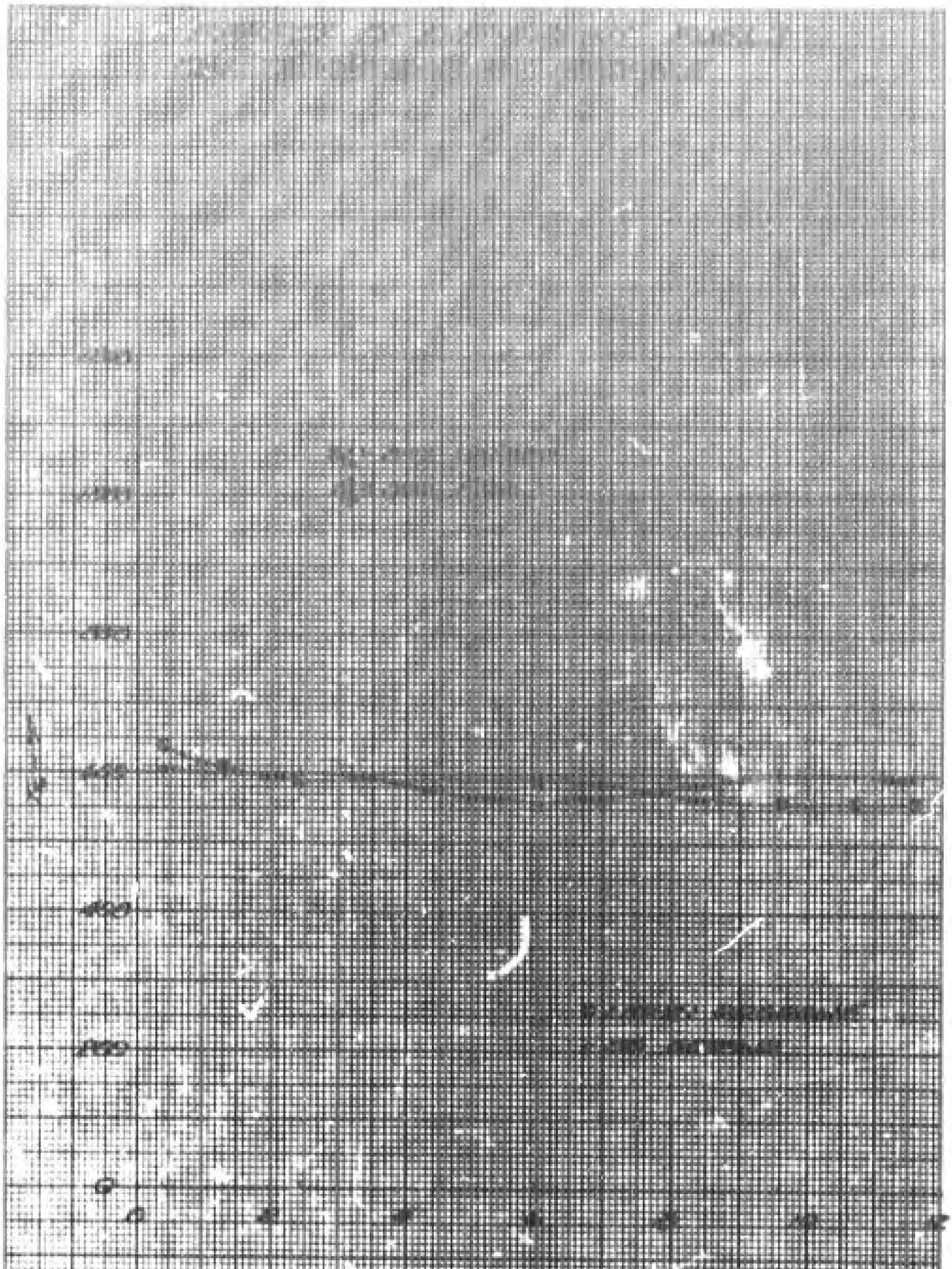

FIGURE 56

5. DISCUSSION OF RESULTS - continued

5.8 The use of spark plugs for ignition was proven feasible. The burner ignited easily with each of the spark plug positions tested, using propane fuel. Repeated ignition attempts and prolonged operation did not damage the spark plugs.

5.9 The overall burner performance shows a marked decrease in combustion efficiency for high air flow (above 100 lb/sec), when using the upstream turbulator. With no turbulator, the efficiency is low for all flows but still exhibits the trend to lower efficiencies at high flows. From this, it can be deduced that the efficiency is a function of the volume upstream of the turbulator. As pointed out in the turbulator evaluation, the turbulator serves to increase the low velocity zone in which burning can be stabilized. It also thoroughly mixes the burned and unburned gasses as they pass through the turbulator orifice. This mixing quenches the flame for the low overall fuel air ratios involved in this series of tests by mixing the fuel and air to below the minimum fuel air ratio for a combustible mixture. Moving the turbulator downstream would provide more volume for burning and allow more of the fuel to burn before the flame was quenched. The optimum location of the turbulator would provide the best efficiency for the range of flows and temperatures desired. In addition, previous testing with an 18" diameter burner confirmed the fact that burners could be scaled with dependable combustion stability. This 18" burner was designed using stability parameters obtained from a 6" diameter model test program. The scale factor in this case was 9:1 (area wise) and is identical to the scale factor between the PLUTO model heater and the full scale PLUTO heater.